

GENERALIZATIONS OF THE KOLMOGOROV-BARZDIN EMBEDDING ESTIMATES

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ABSTRACT. We consider several ways to measure the ‘geometric complexity’ of an embedding from a simplicial complex into Euclidean space. One of these is a version of ‘thickness’, based on a paper of Kolmogorov and Barzdin. We prove inequalities relating the thickness and the number of simplices in the simplicial complex, generalizing an estimate that Kolmogorov and Barzdin proved for graphs. We also consider the distortion of knots. We give an alternate proof of a theorem of Pardon that there are isotopy classes of knots requiring arbitrarily large distortion. This proof is based on the expander-like properties of arithmetic hyperbolic manifolds.

In this paper we study quantitative geometric estimates about embedding different spaces into Euclidean space. The main theme is the connection between topology and geometry: if an embedding is topologically complicated, what kind of geometric estimates does that imply? Our results generalize a theorem by Kolmogorov and Barzdin [KB] from the 1960’s about embedding graphs into \mathbb{R}^3 . Let’s begin by recalling what they did.

Given a topological embedding from a graph Γ into \mathbb{R}^3 , we say that the embedding has thickness at least T if the distance between any non-adjacent edges is at least T , the distance between two vertices is at least T , and the distance from an edge to a vertex not in the edge is at least T . Roughly speaking, one should imagine the vertices as balls of radius T and the edges as (curved) tubes of thickness T . Kolmogorov and Barzdin mention as examples “logical networks and neuron networks” ([KB] page 194). A logical network probably refers to a computer circuit where the edges correspond to wires and the vertices correspond to gates. A neuron network refers to a brain, where the vertices correspond to neurons and the edges correspond to axons connecting the neurons.

Kolmogorov and Barzdin essentially proved the following theorem.

Theorem 1. *If Γ is a graph of degree at most d with N vertices, then Γ may be embedded with thickness 1 into a 3-dimensional Euclidean ball of radius $R \leq C(d)N^{1/2}$.*

On the other hand, let Γ be a random bipartite graph of degree 6 with $2N$ vertices. With high probability (tending to 1), there is no embedding of thickness 1 from Γ into a ball of radius $cN^{1/2}$. Moreover, if we embed Γ into \mathbb{R}^3 with thickness 1, then the volume of the 1-neighborhood of the image is at least $cN^{3/2}$.

This result and its proof contain several interesting geometric ideas. The most important idea is the discovery of expanders. Kolmogorov and Barzdin essentially observed that a random graph is an expander. Then they proved that expanders are hard to embed in Euclidean space.

In this paper, we generalize the work of Kolmogorov and Barzdin in various directions. We will study objects with some properties analogous to expanders, and we will see that they are hard to embed in Euclidean space. We have three main results. The first is a higher-dimensional version of Theorem 1, dealing with embeddings of k -dimensional simplicial complexes into n -dimensional space for $n \geq 2k + 1$. The next two results have to do with the closed arithmetic hyperbolic manifolds - a class of manifolds with some expander-like properties. The second theorem deals with the difficulty of embedding an arithmetic hyperbolic manifold in Euclidean space.

The third result, which is probably the most interesting, deals with certain complicated knots. We recall that a knot K has distortion at least D if there are two points $x, y \in D$ with $\text{dist}_K(x, y) \geq D \text{dist}_{\mathbb{R}^3}(x, y)$. (Here $\text{dist}_K(x, y)$ denotes the distance from x to y along K - the length of the shortest segment of K from x to y .) For a long time, it was an open problem whether there are isotopy classes of knots requiring arbitrarily large distortion. Recently in [P], Pardon gave a lower bound for the distortion of torus knots. In particular, he gave a sequence of torus knots that require arbitrarily large distortion. We give a second proof that there are isotopy classes of knots requiring arbitrarily large distortion. Our proof is based on the geometry/topology of arithmetic hyperbolic 3-manifolds. A closed arithmetic hyperbolic 3-manifold M admits a degree 3 cover of S^3 ramified only over a knot $K(M)$. The ‘expander’-like properties of M imply ‘expander’-like properties of $K(M)$, which we use to show that $K(M)$ has a large distortion.

Now we describe our results in more detail.

First we generalize the theorems of Kolmogorov and Barzdin to higher dimensions. We consider topological embeddings $X^k \rightarrow \mathbb{R}^n$ where X is a k -dimensional simplicial complex. We say that an embedding has combinatorial thickness at least T if the distance between the images of any two non-adjacent simplices is at least T . By a general position argument, X embeds in \mathbb{R}^n for all $n \geq 2k + 1$. We make this more quantitative by estimating the thickness of such an embedding. When $k = 1$ and $n = 3$, our result recovers the Kolmogorov-Barzdin theorem up to small errors.

Theorem 2. *Suppose that $n \geq 2k + 1$ and that each vertex of X belongs to at most L k -faces of X . Suppose that X has N vertices. Then X embeds with thickness 1 into $B^n(R)$ for $R = c(n, L, \epsilon) N^{\frac{1}{n-k} + \epsilon}$.*

On the other hand, for each $n \geq 2k + 1$ and each $\epsilon > 0$, we can find a sequence of k -complexes X_i obeying the following estimates. The complex X_i has $N_i \rightarrow \infty$ simplices. Each vertex in any X_i lies in at most $L(\epsilon)$ simplices of X_i . Here $L(\epsilon)$ is a constant depending on ϵ but uniform among all of the X_i . Finally, if we embed X_i into \mathbb{R}^n with combinatorial thickness ≥ 1 , then the 1-neighborhood of the image has volume at least $c(n, \epsilon) N_i^{\frac{n}{n-k} - \epsilon}$. In particular, if X_i is embedded with combinatorial thickness ≥ 1 into an n -ball of radius R , then $R \geq c(n, \epsilon) N_i^{\frac{1}{n-k} - \epsilon}$.

In order to generalize Kolmogorov and Barzdin’s examples, one might hope to find “higher-dimensional expanders”. We will give this a precise meaning in Section 2. It’s not hard to check that if X^k is a higher-dimensional expander with N simplices, and X is

embedded in an n -ball of radius R , then $R \geq cN^{\frac{1}{n-k}}$. However, we don't know whether such higher-dimensional expanders exist. The examples we consider are the k -skeleta of high-dimensional cubical lattices. These are not as good as expanders, so our lower bound has an extra ϵ that doesn't appear in the Kolmogorov-Barzdin theorem.

Our next theorem involves a different notion of the 'thickness' of an embedding. We say that an embedding $I : X \rightarrow \mathbb{R}^n$ has retraction thickness at least T if the T -neighborhood of $I(X)$ retracts to $I(X)$. When we first formulated it, we thought this definition was just a minor variation of the Kolmogorov-Barzdin definition of combinatorial thickness. But it turns out that retraction thickness has very different properties. For example, an expander graph with N vertices can be embedded with retraction thickness 1 into a 3-ball of radius $\sim N^{1/3}$, much smaller than for combinatorial thickness. The reason for this is roughly that the retraction thickness usually treats homotopic spaces the same, and an expander graph with N vertices is homotopic to a planar graph with N vertices.

We prove several results of the following flavor. If X is homotopically complicated and we embed X in \mathbb{R}^n with retraction thickness at least 1, then the volume of the 1-neighborhood of $I(X)$ should be big. For example, we will prove that the volume of the 1-neighborhood is \gtrsim the sum of Betti numbers of X . Our most interesting result in this direction involves arithmetic hyperbolic manifolds.

Theorem 3. *Let X be a closed arithmetic hyperbolic k -manifold with volume V_{hyp} . Suppose $k \geq 3$. If we embed X in \mathbb{R}^n with retraction thickness 1, then the 1-neighborhood of the image has volume at least $c(k, n)V_{hyp}^{\frac{n}{n-1}}$.*

This theorem also involves expanders in a sense. The key property of arithmetic hyperbolic manifolds is that they obey an expander-type isoperimetric inequality. In particular, they come with natural triangulations and their 1-skeleta are expander graphs. This expander property is exploited in the proof. A non-arithmetic closed hyperbolic 3-manifold with volume V_{hyp} obeys a weaker estimate: the 1-neighborhood of the image has volume $\gtrsim V_{hyp}$.

It's not clear how sharp this theorem is. For example, suppose that we embed our arithmetic hyperbolic 3-manifold X^3 into $B^7(R)$ with retraction thickness at least 1. Our theorem shows that $R \gtrsim V_{hyp}^{1/6}$. On the other hand, we will construct such embeddings with $R \sim V_{hyp}^{1/4+\epsilon}$. We don't know where the optimal value of R lies within this range.

Our last result concerns the geometric properties of complicated knots. A knot is an embedding from $X = S^1$ into \mathbb{R}^3 . In this case, the space X is simple, but we consider complicated isotopy classes of embeddings. The knots we study are built using arithmetic hyperbolic 3-manifolds. To define these knots, we recall the following theorem of Hilden and Montesinos ([H] and [M]).

Ramified cover theorem. *(Hilden, Montesinos) Any closed oriented 3-manifold M admits a degree 3 map $M \rightarrow S^3$ which is a ramified cover ramified over a knot $K = K(M)$.*

Because M is very complicated topologically, it turns out that $K(M)$ must be complicated geometrically. In particular, we prove that $K(M)$ has a large distortion.

Theorem 4. *Let M be a closed arithmetic hyperbolic 3-manifold with volume V . Suppose that M is a 3-fold cover of S^3 ramified over a knot $K(M)$. Then $K(M)$ has distortion at least cV . (And so does any knot isotopic to $K(M)$.)*

In particular, we see that there are isotopy classes of knots requiring arbitrarily large distortion.

There are many different ways to measure the “geometric complexity” of an embedding. We consider several different measures of complexity, related to combinatorial thickness, retraction thickness, and distortion. Each of these ways of measuring geometric complexity leads to different kinds of estimates. There are many open questions along these lines, and some of them are indicated in the paper at the end of each section.

In the first section of the paper, we discuss the work of Kolmogorov and Barzdin. In the second section of the paper, we discuss embeddings of higher dimensional complexes and prove Theorem 2. In the third section, we discuss embeddings of homotopically complicated spaces and prove Theorem 3. In the fourth section, we discuss the distortion of knots and prove Theorem 4. The different sections are mostly independent. In an appendix we review some fundamental facts about the geometry and topology of arithmetic hyperbolic manifolds. In particular, we emphasize the expander-type properties of these manifolds and the connections between expanders and topology.

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1. EMBEDDING NETWORKS IN EUCLIDEAN SPACE

In this section, we discuss the paper “On the realization of networks in three-dimensional space” by Kolmogorov and Barzdin. In Section 1.1, we summarize the main ideas of the paper. We give detailed proofs of any results that we need later on. In Section 1.2, we make some historical comments.

1.1. Embedding graphs in \mathbb{R}^3 . Suppose that Γ is a graph, and $I : \Gamma \rightarrow \mathbb{R}^3$ is a topological embedding of Γ in three-dimensional Euclidean space. We think of Γ as a simplicial complex of dimension 1. We say that the embedding I has combinatorial thickness at least T if $\text{dist}[I(\Delta_1), I(\Delta_2)] \geq T$ whenever Δ_1 and Δ_2 are non-adjacent simplices of Γ . (Here Δ_i is either a vertex of Γ or an edge of Γ . So we see that the distance between any two distinct vertices is at least T , and the distance between any two edges that don’t share a vertex is at least T , and the distance between an edge and a vertex not in the edge is at least T .)

For a first perspective, suppose that the graph Γ is an $N^{1/2} \times N^{1/2}$ grid. It is easy to embed Γ with combinatorial thickness 2 into a block of dimensions $10 \times 10N^{1/2} \times 10N^{1/2}$. Moreover, we can assume that the distance from Γ to the edge of the block is at least 2. This block can in turn be folded up to fit in a ball. More precisely, there is an embedding Ψ from the block into a ball of radius $100N^{1/3}$ which is locally 2-bilipschitz. This means that Ψ stretches vectors by at most a factor of 2 and contracts vectors by at most a factor of 2. In particular, the image $\Psi(\Gamma)$ has combinatorial thickness at least 1. So we see that a grid admits an embedding of thickness 1 into a ball of radius only $\sim N^{1/3}$. But it turns out

that other graphs of bounded degree are much harder to embed than grids. These other graphs are expanders, and we discuss them more below.

In [KB], Kolmogorov and Barzdin proved that random graphs are the hardest graphs to embed and gave a sharp estimate for the thickness of embedded graphs. They essentially proved Theorem 1 from the introduction. For convenience, we copy the statement here.

Theorem 1. *If Γ is a graph of degree at most d with N vertices, then Γ may be embedded with thickness 1 into a 3-dimensional Euclidean ball of radius $R \leq C(d)N^{1/2}$.*

On the other hand, let Γ be a random bipartite graph of degree 6 with N vertices. With high probability (tending to 1), there is no embedding of thickness 1 from Γ into a ball of radius $cN^{1/2}$. Moreover, if we embed Γ into \mathbb{R}^3 with thickness 1, then the volume of the 1-neighborhood of the image is at least $cN^{3/2}$.

In the first part of their paper, Kolmogorov and Barzdin construct thick embeddings from Γ to $B(R)$, $R = C(d)N^{1/2}$. The vertices of their graph are mapped to the boundary of the ball. According to Arnold's reminiscences of Kolmogorov, the original motivation for the research was the study of the brain [A]. Kolmogorov had heard that all neurons are located at the edge of the brain and that the large center of the brain consists of axons between the neurons. The embedding they construct has the same architecture: the vertices lie on the edge of the ball, and the edges fill up the inside of the ball. After placing the vertices evenly around the boundary of the ball, in an arbitrary order, they construct the edges of the graph one at a time. Each edge is a piecewise linear curve depending on a couple of parameters. By a counting argument, they show that at each step they can choose these parameters to avoid all of the previous edges.

They prove that this construction is sharp for random graphs. To do this, they prove that random graphs are expanders with high probability. Recall that a graph Γ is called an α -expander if it obeys the following isoperimetric inequality: if A is a subset of the vertices of Γ with at most half of the vertices, then the number of edges from A to the complement of A is at least $\alpha|A|$. There exists a constant $\alpha > 0$ so that a random bipartite graph of degree 6 with N vertices is an α -expander with probability tending to 1 as N goes to infinity. (Kolmogorov and Barzdin proved something very similar to this - see Section 1.2 for more information. The expander properties of random graphs are discussed in detail in [HLW].)

Suppose that Γ is an α -expander with degree 6 and N vertices, embedded with thickness 1 into a ball of radius R . Slice the ball into horizontal planes $z = h$. By choosing h , we can arrange that at least half of the points lie in the region $\{z \geq h\}$ and at least half lie in $\{z \leq h\}$. Let V^+ denote the vertices in $\{z \geq h\}$ and V^- the vertices in $\{z \leq h\}$. By the expander property, there are $\geq (1/2)\alpha N$ edges of the graph from V^+ to V^- , and each of these edge must intersect the plane $z = h$. Any edge shares a vertex with $\leq 2d$ other edges, and so we can choose $\gtrsim N$ edges of Γ passing through $\{z = h\}$ with no two edges sharing a vertex. By definition of combinatorial thickness, the unit neighborhoods around these edges are disjoint. Let D denote the disk given by intersecting the ball $B^3(R)$ with the plane $\{z = h\}$. It has radius at most R , yet it contains $\gtrsim N$ points pairwise separated by a distance of at least 1. So we see that $N \lesssim R^2$, and so the radius R is $\gtrsim N^{1/2}$. Therefore,

the radius in the construction of Kolmogorov-Barzdin cannot be improved by more than a constant factor.

Next we turn to the volume of the 1-neighborhood of $I(\Gamma)$. We write $U := N_1(I(\Gamma))$ to denote the radius 1 neighborhood of the image $I(\Gamma)$. If the embedding I has thickness 1, we need to prove that the volume of U is $\gtrsim N^{3/2}$. To do this, we will again find a plane that bisects the vertices of Γ . We find the plane using the Falconer slicing inequality [F].

Falconer Slicing Estimate. *Let U be an open set in \mathbb{R}^n . If $k > n/2$, then we can slice U with parallel k -planes so that the intersection of U with each plane has k -area at most $C_n \text{Vol}[U]^{k/n}$.*

In our case, $n = 3$ and $k = 2 > n/2$, and so we can slice U into parallel planes so that each plane intersects U in area $\lesssim \text{Vol}(U)^{2/3}$. One of the planes bisects the vertices of Γ , and we can conclude by the argument above that $N \lesssim \text{Vol}(U)^{2/3}$.

For context, we briefly discuss the values of k and n in Falconer's inequality. The restriction on k in Falconer's estimate is not well-understood. If $k = 1$, the theorem is definitely false because of a construction of Besicovitch. For $2 \leq k \leq n/2$, I believe it's an open problem whether the theorem still holds. In all of our applications, we will have $k > n/2$. Nevertheless, for smaller values of k , U may be swept out by curved k -dimensional surfaces of small area as shown in [Gu].

1.2. Historical comments. Expander graphs are an important object in mathematics. At the first or second encounter, it seems very surprising that they exist. They have applications in many areas, including computer science, geometry, and number theory. The essay [HLW] gives a thorough expository account of this area. Expander graphs also have some applications in topology which we discuss more in the appendix.

The first proof that expanders exist is usually cited as Pinsker's proof, published in 1973 [Pi]. But the paper [KB] of Kolmogorov and Barzdin also essentially proves that a random graph is an expander. It was published in 1967.

Kolmogorov began to work on the graph embedding project in the early 1960's. He did the graph embedding construction described above. Then he gave an example where an embedding of thickness 1 required a ball of volume $N^{3/2}/\log N$. We don't know what example Kolmogorov was using. Later, Barzdin joined the project and proved the sharper estimate $N^{3/2}$.

Strictly speaking, Kolmogorov and Barzdin studied directed graphs where the number of incoming edges at each vertex was always d (say $d = 2$), but the number of outgoing edges could vary. If we consider these graphs as undirected graphs, the degree is not actually bounded. Random directed graphs are easy to define. Each vertex has d incoming edges, and each of these edges is assigned a starting vertex uniformly at random. (It looks plausible that Kolmogorov and Barzdin work with directed graphs because it is easier to define a random directed graph.) A random directed graph with $d = 2$ and N vertices typically has a few vertices with something like $\log N$ outgoing edges. If we look at them as undirected graphs, they typically don't have bounded degree. Still, the results of Kolmogorov and Barzdin come very close to producing expander graphs of uniformly bounded degree. For

example, their graphs do have bounded average degree. Probably one can build bounded-degree expanders by a short additional argument that prunes the high-degree vertices and a few other vertices from these graphs.

Barzdin's recollections of the paper are interesting. These appear in the notes section of the collected works of Kolmogorov [B]. Kolmogorov credits Barzdin with the "very idea of setting the question of almost all graphs". It sounds like Barzdin had the idea of looking at random graphs and proving that most of them are expanders. Barzdin writes modestly, "In fact I only gave new proofs (and somewhat generalized) theorems obtained by Andrei Nikolayevich earlier, so that my achievements here are not very important."

On the origins of the paper, Barzdin writes, "Unfortunately, I don't remember what was the occasion or event at which Andrei Nikolayevich first mentioned these results (I was not present there). I know only that the topic discussed there was the explanation of the fact that the brain (for example that of a human being) is so constituted that most of its mass is occupied by nerve fibers (axons) while the neurons are only disposed on its surface. The construction of Theorem 1 precisely confirms the optimality (in the sense of volume) of such a disposition of the neuron network."

The paper [KB] has possible connections with other parts of science. Kolmogorov and Barzdin write, "Examples of such networks are logical networks and neuron networks. It is precisely for this reason that the question of constructing such networks in ordinary three-dimensional space under the condition that the vertices are balls while the edges are tubes of a certain positive diameter is of importance." We don't know whether connections with neuroscience or computer science have been pursued. On the neuroscience side, to what extent is it true that the neurons of the brain lie on the boundary of a ball with the axons going through the interior of the ball? To what extent is the 'graph' of the brain an expander? Another possible connection is with the design of computer chips. In his essay [A], Arnold writes, "It is interesting to note that this paper [KB] has remained little known even to specialists, perhaps because the mathematical exposition is too serious. When I mentioned it in a paper in *Physics Today* dedicated to Kolmogorov (October 1989), I received a sudden deluge of letters from American engineers who were apparently working in miniaturization of computers, with requests for a precise reference to his work." How do engineers design the 3-dimensional structure of computer chips? Are the underlying graphs expanders?

There is a substantial literature on the geometry of computer chips, which I know little about. Paule Beame pointed me to the paper [BK] by Brent and Kung which studies the geometry of a computer chip which multiplies two n -digit binary numbers. Brent and Kung give sharp estimates involving the area and running time of the computer chip.

(The computer circuits that Brent and Kung study are laid out in planar domains with $\lesssim 1$ wires crossing at any point in the planar domain. Nearly planar arrangements of wires are not good for embedding expanders in space. If an expander graph Γ is embedded with thickness 1 into a rectangular box with dimensions $A \times B \times C$, $A \leq B \leq C$, then the number of vertices of Γ is $\lesssim AB$ - it is bounded by the smallest cross-sectional area of the box. In particular, if Γ has N vertices, then it may embed into a box of dimensions $10 \times L \times L$ only if $L \gtrsim N$, and only if the box has volume $\gtrsim N^2$. Brent and Kung explain

the nearly planar arrangement of computer circuits: “Because of heat-dissipation, packing, and testing requirements, a two-dimensional planar model is reasonable.”)

2. EMBEDDINGS OF HIGHER-DIMENSIONAL COMPLEXES

In this section, we generalize the upper and lower bounds of Kolmogorov-Barzdin to embeddings from k -dimensional simplicial complexes into \mathbb{R}^n for $n \geq 2k + 1$.

Suppose that X is a simplicial complex and $I : X \rightarrow \mathbb{R}^n$ is an embedding. We say that I has combinatorial thickness $\geq T$ if the distance between $I(\Delta_1)$ and $I(\Delta_2)$ is at least T for any two non-adjacent simplices of X . These simplices may have any dimension - they don't need to be top-dimensional. Two simplices are non-adjacent if they share no vertices, or equivalently if their closures are disjoint.

We prove if $n \geq 2k + 1$, then any simplicial complex X^k with N simplices and bounded local geometry can be embedded with combinatorial thickness 1 into an n -ball of radius $\lesssim N^{\frac{1}{n-k}+\epsilon}$, and we prove that this estimate is sharp up to factors of N^ϵ . In Section 2.1, we construct the embeddings. In Section 2.2, we give examples when the estimate is nearly sharp. In Section 2.3, we discuss open problems.

2.1. Constructing embeddings. Suppose that X is a simplicial complex of dimension k . For $n \geq 2k + 1$, the complex embeds in \mathbb{R}^n by general position arguments. We will estimate the radius of a ball $B^n(R)$ so that X embeds with combinatorial thickness 1 into $B^n(R)$. Our proof is a quantitative version of the standard general position argument. But there is one subtlety: we need to do a quantitative general position argument at two different scales.

For $k = 1$, $n = 3$, Kolmogorov and Barzdin proved that a graph with degree $\leq d$ admits an embedding with thickness 1 into a ball of radius $R \sim C(d)N^{1/2}$. Their method generalizes immediately to $k = 1$ and any $n \geq 3$. In higher dimensions, the radius goes like $R \sim C(d)N^{\frac{1}{n-1}}$. This exponent is sharp for all $n \geq 3$ when X is an expander.

In higher dimensions, the right generalization appears to be the following:

Conjecture. *Suppose that X is a k -dimensional simplicial complex with N simplices, and that each vertex lies in $\leq L$ simplices. Suppose that $n \geq 2k + 1$. Then there is a 1-thick embedding from X into the n -dimensional ball of radius*

$$R \leq C(n, L)N^{\frac{1}{n-k}}.$$

When $k = 1$, this conjecture agrees with the Kolmogorov-Barzdin embedding construction, and when $k = 0$ it is easy to check. In all dimensions, we prove this conjecture up to some logarithmic factors.

Theorem 2.1. *Suppose that X is a k -dimensional simplicial complex with N vertices and each vertex lying in at most L simplices. Suppose that $n \geq 2k + 1$. Then X embeds with combinatorial thickness 1 into the n -dimensional ball of radius*

$$R \leq C(n, L)N^{\frac{1}{n-k}}(\log N)^{2k+2}.$$

We first consider random facewise linear embeddings. A random facewise linear embedding means that we first map each vertex of X randomly to a point in a given ball. Then we extend the map linearly on each simplex. Random facewise linear embeddings have thickness much too small to prove our theorem, but we will construct our embedding by modifying a random facewise linear embedding. To get a perspective, we first compute the thickness of a random facewise linear embedding.

Proposition 2.1. *Let X be a k -dimensional simplicial complex with N simplices. Suppose that $n \geq 2k + 1$. A random face-wise linear embedding from X into the n -dimensional ball of radius R is usually T -thick for*

$$T \sim RN^{-\frac{2}{n-2k}}.$$

In particular, we can find a 1-thick embedding if

$$R \gtrsim N^{\frac{2}{n-2k}}.$$

Proof. Fix Δ, Δ' simplices in X of dimensions $d, d' \leq k$. Suppose that their vertex sets are disjoint. Then the probability that the distance from $I(\Delta)$ to $I(\Delta')$ is less than T is roughly $(T/R)^{n-d-d'} \leq (T/R)^{n-2k}$. Now the number of pairs of simplices is at most N^2 , and so we get a T -thick embedding most of the time provided that

$$C(n)N^2(T/R)^{n-2k} < 1/2.$$

□

This random embedding is not nearly as good as the Kolmogorov-Barzdin embedding in case $k = 1$. We will improve it by bending the simplices at a smaller scale. Roughly speaking, we will put our map in general position at scale $N^{\frac{1}{n-k}}$ and also at scale 1. Now we turn to the detailed construction of our embedding.

Proof. We write $A \lesssim B$ for $A \leq C(n, L)B$.

Let I_0 be a random facewise linear embedding from X into $B^n(N^{\frac{1}{n-k}})$. We will deform I_0 to an embedding with thickness $\gtrsim (\log N)^{-(2k+2)}$. To begin our analysis, we count how many simplices meet unit balls $B(p, 1) \subset B^n$.

Lemma 2.2. *With high probability, each unit ball $B(p, 1) \subset B(N^{\frac{1}{n-k}})$ meets $\lesssim \log N$ simplices of $I_0(X)$.*

Proof. Fix a ball $B(p, 1)$ and a simplex $\Delta^d \subset X$. The probability that $I_0(\Delta^d)$ meets $B(p, 1)$ is $\lesssim N^{-1}$. We can see this as follows. The probability is essentially independent of which ball $B(p, 1)$ we are considering. So we can first pick $I_0(\Delta^d)$ and then pick a random p and look at the probability that $B(p, 1)$ meets $I_0(\Delta^d)$. We consider the projection into the plane orthogonal to $I_0(\Delta^d)$. If $B(p, 1)$ meets $I_0(\Delta^d)$, then the projection of p into this plane needs to lie within a unit distance of the point corresponding to $I_0(\Delta^d)$. Now the projection of p is basically equally likely to lie anywhere in a ball of radius $R = N^{\frac{1}{n-k}}$ and dimension $n - d \geq n - k$.

Therefore, the expected number of simplices hitting $B(p, 1)$ is $\lesssim 1$. But some balls may meet more simplices than average.

Label the simplices of X $\Delta_1, \Delta_2, \dots$. Consider the event that Δ_i meets $B(p, 1)$. If these events were independent, then the probability of having A simplices meet $B(p, 1)$ would decay $\leq \binom{N}{A} (C/N)^A \leq C^A / (A!) \leq e^{-A}$ for large A . If that were true, then with high probability, the number of simplices hitting $B(p, 1)$ would be $\lesssim \log N$ for every p .

If a set of simplices has no common vertices, then the positions of the simplices really are independent. So we can finish with a coloring trick. Color the simplices of X so that any two simplices sharing a vertex are a different color. Let β denote the number of colors. Because each vertex lies in $\lesssim L$ simplices, we can bound the number of colors by $(k+1)L$. With high probability, the number of simplices of each color meeting $B(p, 1)$ is $\lesssim \log N$ for each p . Since the number of colors is $\lesssim 1$, we are done. \square

The number of different simplices that intersect a unit ball $B(p, 1) \subset B^n(N^{\frac{1}{n-k}})$ is $\lesssim \log N$. In some unlucky balls, these simplices pass extremely close to each other. We are going to bend the simplices at scale 1 to fix this problem. By putting simplices in general position within each unit ball, we will show that they don't need to be any closer to each other than $(\log N)^{-(2k+2)}$.

In order to bend the simplices, we need to decompose each simplex into finer simplices.

Simplex decomposition lemma. *We can refine the simplicial complex $I(X)$ into a finer complex X' with the following properties.*

1. *Each simplex of X' has diameter $\lesssim 1$.*
2. *Each vertex of X' lies in $\lesssim L$ simplices of X' .*
3. *Each unit ball in \mathbb{R}^n intersects $\lesssim \log N$ simplices of X' .*

Proof. Intersect the complex X with a unit cubical lattice K . This leads to a polyhedral structure on X which refines the original simplicial structure. Each face of the new structure lies in a unit cube, so it has diameter $\lesssim 1$. The number of faces of $\Delta \cap K$ which meet a unit ball is $\lesssim 1$. Now the faces of this polyhedral structure may not be simplices, but we subdivide them each into simplices. The number of simplices needed to triangulate each face is $\lesssim 1$, because there are only finitely many combinatorial possibilities for the faces. If each vertex of X lies in $\leq L$ simplices, then each vertex of X' lies in $\leq CL$ simplices.

Each unit ball in \mathbb{R}^n intersects $\lesssim \log N$ simplices of X . Let Δ be any simplex of X that intersects $B(p, 1)$. The intersection $\Delta \cap B(p, 1)$ is contained in $\lesssim 1$ simplices of X' . \square

The complex X' is homeomorphic to X , with each simplex of X corresponding to many simplices of X' .

We now move each vertex of the refined simplicial complex X' by a vector of length ≤ 1 , and we extend linearly on the refined simplices. In this way, we get a map $I : X' \rightarrow B(N^{\frac{1}{n-k}} + 1)$. We will check that for a good choice of these vectors, the combinatorial thickness of I is $\gtrsim (\log N)^{-(2k+2)}$.

There is a slight issue with language at this point. The map I is an embedding from X' to \mathbb{R}^n and we can also view it as an embedding from X to \mathbb{R}^n . The combinatorial thickness

depends on whether we use the simplicial structure of X or the simplicial structure of X' . Since X' is a refinement of X , the combinatorial thickness with respect to X' is at most the combinatorial thickness with respect to X . We state this as a lemma.

Lemma 2.3. *Suppose that X' is a refinement of X . Let $I : X' \rightarrow \mathbb{R}^n$ be an embedding. Let T' denote the combinatorial thickness of I as an embedding from X' to \mathbb{R}^n , and let T denote the combinatorial thickness of I as an embedding from X to \mathbb{R}^n . Then $T' \leq T$.*

Proof. Consider two non-adjacent simplices Δ_1, Δ_2 in X . Let d denote the distance from $I(\Delta_1)$ to $I(\Delta_2)$. We can find points p_1 in the closure of Δ_1 and p_2 in the closure of Δ_2 so that $|I(p_1) - I(p_2)| = d$. Let $\Delta'_1 \subset \Delta_1$ be the smallest simplex of X' containing p_1 , and similarly for p_2 . Since X' is a refinement of X , the simplex Δ'_1 is contained in the closure of Δ_1 and Δ'_2 is contained in the closure of Δ_2 . Hence Δ'_1 and Δ'_2 are non-adjacent. We conclude that d is at least the distance between $I(\Delta'_1)$ and $I(\Delta'_2)$ which is at least T' . So $T \geq T'$. \square

Therefore, it suffices to choose I so that the combinatorial thickness of $I : X' \rightarrow B(N^{\frac{1}{n-k}} + 1)$ is $\gtrsim (\log N)^{-(2k+2)}$.

Let $\{v_i\}$ denote the vertices of X' . We will define $I(v_i)$ one vertex at a time, and then extend I linearly to each simplex of X' . We will choose $I(v_i)$ in the unit ball around $I_0(v_i)$. Let $Con(i)$ denote this unit ball with probability measure given by renormalizing the volume measure. Then let Con denote the product $\prod Con(i)$ with the product measure. Here Con is the configuration space of all of our choices, and we have to find an element of Con so that the thickness of I is pretty big. (Remark: A random element of Con does not usually have the desired properties, but introducing this probability measure is still useful in our proof.)

For simplices $\Delta_1, \Delta_2 \subset X'$ with no common vertices, we define $Bad_\epsilon(\Delta_1, \Delta_2)$ to be the set of all the configurations where the distance from $I(\Delta_1)$ to $I(\Delta_2)$ is $\leq \epsilon$. We will choose an $\epsilon \sim (\log N)^{-(2k+2)}$, and it suffices to find a configuration which does not lie in any of the sets $Bad_\epsilon(\Delta_1, \Delta_2)$.

The main helpful point is that many of the sets $Bad_\epsilon(\Delta_1, \Delta_2)$ are empty. If $dist(\Delta_1, \Delta_2) > 3$, then no matter how we move the vertices by distances < 1 , $I(\Delta_1)$ and $I(\Delta_2)$ will still be separated by at least 1. Since we will choose $\epsilon < 1$, $Bad_\epsilon(\Delta_1, \Delta_2)$ will be empty. From now on, we only discuss the non-empty sets $Bad_\epsilon(\Delta_1, \Delta_2)$. By Lemma 2.2 and the simplex decomposition lemma, there are $\lesssim \log N$ simplices of X' in any ball of radius 10. In particular, for each vertex v_i , there are $\lesssim \log N$ non empty sets $Bad_\epsilon(\Delta_1, \Delta_2)$ where v_i lies in Δ_1 or Δ_2 .

We can also estimate the probability of $Bad_\epsilon(\Delta_1, \Delta_2)$ in the non-empty case.

Lemma 2.4. *For any simplices Δ_1, Δ_2 with no vertex in common, the probability of $Bad_\epsilon(\Delta_1, \Delta_2)$ is $\lesssim \epsilon$.*

This lemma is similar to the analysis of a random facewise linear embedding. There is also a formal proof later in Proposition 3.12.

Now we choose v_1 , then v_2 , etc. As we make each choice, we keep track of the conditional probability of the sets $Bad_\epsilon(\Delta_1, \Delta_2)$, given the choices we have made so far. This analysis is similar to the Lovasz local lemma in [EL].

When we pick v_i , the conditional probability of $Bad_\epsilon(\Delta_1, \Delta_2)$ changes only if v_i is a vertex of Δ_1 or Δ_2 . So the choice of v_i affects $\lesssim \log N$ conditional probabilities. The odds of increasing any conditional probability by a factor A are $\leq (1/A)$. Therefore, we can choose v_i so that the conditional probabilities of $Bad_\epsilon(\Delta_1, \Delta_2)$ increase by at most a factor $\lesssim \log N$, when v_i is a vertex of Δ_1 or Δ_2 .

Each pair (Δ_1, Δ_2) has in total $\leq 2k + 2$ vertices. Therefore, after we have chosen all v_i , the conditional probability of $Bad_\epsilon(\Delta_1, \Delta_2)$ has increased by a factor $\lesssim (\log N)^{2k+2}$. Since the probability of $Bad_\epsilon(\Delta_1, \Delta_2)$ was $\lesssim \epsilon$ before making any choices, after all our choices, the conditional probability of $Bad_\epsilon(\Delta_1, \Delta_2)$ is $\lesssim \epsilon(\log N)^{2k+2}$. Of course, once we have chosen all $I(v_i)$, the conditional probability of $Bad_\epsilon(\Delta_1, \Delta_2)$ is either 1 or 0, depending on whether our choice lies in $Bad_\epsilon(\Delta_1, \Delta_2)$ or not. We pick ϵ sufficiently small so that all conditional probabilities of $Bad_\epsilon(\Delta_1, \Delta_2)$ are < 1 . This ϵ is $\sim (\log N)^{-(2k+2)}$. Now our choice of the map I does not lie in any of the sets $Bad_\epsilon(\Delta_1, \Delta_2)$. In other words, the embedding $I : X' \rightarrow B(N^{\frac{1}{n-k}})$ has combinatorial thickness $\geq \epsilon \gtrsim (\log N)^{-(2k+2)}$. \square

2.2. Complexes that are hard to embed in Euclidean space. In this section, we prove that some complexes are hard to embed in Euclidean space. Our result generalizes the result of Kolmogorov and Barzdin that some graphs are hard to embed in \mathbb{R}^3 , but our estimate is a little less sharp than theirs.

Theorem 2.2. *Fix k and n with $n \geq 2k + 1$. For any $\epsilon > 0$, there is a constant $L(\epsilon)$, and a sequence of k -dimensional simplicial complexes X_i with the following properties.*

Each vertex in each X_i belongs to $\leq L(\epsilon)$ simplices.

The number of simplices in X_i is $N_i \rightarrow \infty$.

If X_i is embedded into \mathbb{R}^n with combinatorial thickness 1, then the 1-neighborhood of the image has volume at least $N_i^{\frac{n}{n-k}-\epsilon}$.

A key fact in the argument of Kolmogorov and Barzdin is that if we map an expander graph to \mathbb{R} , then one of the fibers of the map intersects many edges. Based on this observation, we define a combinatorial width of k -dimensional complexes.

If X is a k -dimensional simplicial complex, we say that X has combinatorial width $\geq W$ (over \mathbb{R}^k) if any continuous map $F : X \rightarrow \mathbb{R}^k$ has a fiber that intersects $\geq W$ closed k -simplices of X . We illustrate the definition with two examples.

Example 1. If X is an expander graph with N vertices and expansion constant h , then the combinatorial width of X over \mathbb{R}^1 is $\geq hN/2$. (proof. pick $y \in \mathbb{R}$ to be the smallest number so that at least half of the vertices of X are mapped to $(-\infty, y]$. We let $V_- \subset X$ denote the vertices of X mapped to $(-\infty, y]$ and V_+ denote the vertices mapped to $[y, +\infty)$. By the expansion property, there are at least $Nh/2$ edges from V_- to V_+ . The image of each of these (closed) edges contains y .)

Example 2. If X is the k -skeleton of the N -simplex, then the number of k -faces of X is $\binom{N+1}{k+1}$. It is shown in [Gr2] that the combinatorial width of X over \mathbb{R}^k is at least $c_k \binom{N+1}{k+1}$.

We can relate the thickness of embeddings and the combinatorial width, basically following Kolmogorov and Barzdin.

Proposition 2.5. *Suppose that X is a k -dimensional simplicial complex and that each vertex lies in at most L k -simplices. Let W denote the combinatorial width of X over \mathbb{R}^k . Let I be an embedding of X into \mathbb{R}^n with combinatorial thickness at least 1. We also assume that $n \geq 2k + 1$. Then the 1-neighborhood of $I(X)$ has volume $\gtrsim L^{-\frac{n}{n-k}} W^{\frac{n}{n-k}}$.*

Proof. Let X^+ denote the 1-neighborhood of $I(X)$, and let V be its volume. By the Falconer slicing estimate, we can map \mathbb{R}^n into \mathbb{R}^k so that each fiber meets X^+ in an area at most $C(k, n) V^{\frac{n-k}{n}}$. One of these fibers intersects at least W simplices in $I(X)$. The number of k -simplices in X that share a vertex with a given k -simplex is at most $(k+1)L$. Therefore, we can find $WL^{-1}(k+1)^{-1}$ simplices in the fiber which do not share any vertices. Hence the slice must contain $\geq (k+1)^{-1}WL^{-1}$ disjoint unit balls. So we see that $V^{\frac{n-k}{n}} \gtrsim L^{-1}W$. \square

Remark: We used the condition $n \geq 2k + 1$ in the proof in order to apply the Falconer slicing estimate. But the result is probably true for all k, n .

If we apply Proposition 2.5 to expanders, we recover the estimate of Kolmogorov and Barzdin. Namely, if X is an expander of degree $\lesssim 1$ and expansion constant h , we see that the 1-neighborhood of $I(X)$ has volume $\gtrsim |X|^{\frac{n}{n-1}}$. We can also apply Proposition 2.5 to the k -skeleton of the N -simplex. Each vertex lies in $\lesssim N^k$ k -simplices. The width W is $\gtrsim N^{k+1}$. Therefore, the volume of the 1-neighborhood is at least $N^{\frac{n}{n-k}}$. (Is it sharp?)

It would be interesting to know if there are k -dimensional complexes X with locally bounded geometry and large combinatorial width, generalizing the expander graphs. More precisely, can we find a sequence of k -dimensional complexes X_i containing $N_i \rightarrow \infty$ k -simplices so that each vertex of X_i lies in $\leq L$ k -simplices and the width of $X_i \geq \alpha N_i$? (Here $L < \infty$ and $\alpha > 0$ are constants, not depending on i .) This question was raised in [Gr2]. It is open. There are some partial results of different kinds in [FGLNP] and [Gr2].

The X_i that we use to prove Theorem 2.2 are the k -skeleta of D -dimensional lattices for large D . These examples are not quite as good as expanders, which leads to the ϵ in the statement of Theorem 2.2.

Let $X^{k,D}(S)$ denote the k -skeleton of the D -dimensional cubical lattice with lattice spacing 1 restricted to a grid of side length S . This $X^{k,D}(S)$ is a cubical complex. The definitions of combinatorial width for cubical complexes is analogous to the definition for simplicial complexes. We will estimate the combinatorial width of $X^{k,D}(S)$ as a cubical complex.

We will pick a large but fixed D and then study the asymptotics of the spaces $X^{k,D}(S)$ as $S \rightarrow \infty$. The complex $X^{k,D}(S)$ has $\sim c(D, k)S^D$ cubical faces (of all dimensions $0 \leq j \leq k$). Each vertex lies in $\leq L(D, k)$ faces.

Proposition 2.6. *The combinatorial width of $X^{k,D}(S)$ over \mathbb{R}^k is $\geq c(D, k)S^{D-k}$.*

Using Proposition 2.6, we can quickly finish the proof of Theorem 2.2.

Proof of Theorem 2.2. We fix D sufficiently large, and then study the sequence of complexes $X^{k,D}(S)$ as $S \rightarrow \infty$. Since the statement of Theorem 2.2 involves simplicial complexes, we subdivide each cubical complex $X^{k,D}(S)$ to get a simplicial complex $X_{simp}^{k,D}(S)$.

Let us write $W(S)$ to abbreviate the combinatorial width of $X_{simp}^{k,D}(S)$, and let us write $N(S)$ to abbreviate the number of simplices in $X_{simp}^{k,D}(S)$.

The combinatorial width of $X_{simp}^{k,D}(S)$ is at least as big as the combinatorial width of $X^{k,D}(S)$. By Proposition 2.6, $W(S) \geq c(D, k)S^{D-k}$.

On the other hand, $X_{simp}^{k,D}(S)$ has $\leq C(D, k)S^D$ faces, so $N(S) \leq C(D, k)S^D$. Therefore, $W(S) \geq c(D, k)N(S)^{\frac{D-k}{D}}$. We choose $D = D(\epsilon, k)$ sufficiently large so that $W(S) \geq c(\epsilon, k)N(S)^{1-\epsilon}$.

The local geometry of $X_{simp}^{k,D}(S)$ depends only on k and D . In particular, each vertex of $X^{k,D}(S)$ lies in $\leq L(D, k)$ simplices of $X_{simp}^{k,D}(S)$.

Now we apply Proposition 2.5. If I is an embedding from $X_{simp}^{k,D}(S)$ into \mathbb{R}^n with combinatorial thickness ≥ 1 , then the 1-neighborhood of the image of I has volume at least $c(D, k)W(S)^{\frac{n}{n-k}} \geq c(D, k)N(S)^{\frac{n}{n-k}-\epsilon}$. \square

In the remainder of Section 2.2, we explain the proof of Proposition 2.6, our estimate for the combinatorial width of $X^{k,D}(S)$. This combinatorial width estimate is a combinatorial analogue of a purely geometric estimate for the width.

Width of the cube. *If $F : [0, S]^D \rightarrow \mathbb{R}^k$ is a generic smooth map, then one of the fibers of F has $(D - k)$ -volume at least $c(D, k)S^{D-k}$.*

(This geometric theorem was proven by Almgren using minimal surface theory. In [Gr3], there is a more elementary proof using isoperimetric inequalities. See [Gu] for more details.) In [Gr2], the isoperimetric proof was adapted to the combinatorial setting. Instead of using classical isoperimetric inequalities, this method uses filling inequalities for cochains. Let's recall what a filling inequality is.

Let X denote a k -dimensional polyhedral complex. We let $C^*(X, \mathbb{Z}_2)$ denote the polyhedral cochains of X . For a polyhedral j -cochain α , we define $\|\alpha\|_1$ to be the number of j -faces in the support of α . Now we define the constant $Fill(j)$ to be the smallest number so that any coboundary $\alpha \in C^j(X, \mathbb{Z}_2)$ has a “filling” $\beta \in C^{j-1}(X, \mathbb{Z}_2)$ so that $d\beta = \alpha$ and $\|\beta\|_1 \leq Fill(j)\|\alpha\|_1$. (For a finite complex X , the constant $Fill(j)$ is finite, but for an infinite complex, it could be $+\infty$.)

The combinatorial width of a complex can be controlled in terms of its filling inequalities by the following theorem.

Width and filling. ([Gr2]) *Suppose that X is a k -dimensional simplicial complex or cubical complex with N vertices. Suppose X is connected and $H^j(X, \mathbb{Z}_2) = 0$ for $1 \leq j \leq k-1$. Let W be the combinatorial width of X over \mathbb{R}^k . Then the following inequality holds.*

$$W \geq c_k \left[\prod_{j=1}^k \text{Fill}(j) \right]^{-1} N. \quad (**)$$

(For explanation and proof see [Gr2] and [D].)

The spaces $X^{k,D}(S)$ are connected and have vanishing homotopy and cohomology groups in dimensions $1 \leq j \leq k-1$, so this inequality applies to them. We now bound the filling constants of the spaces $X^{k,D}(S)$.

Proposition 2.7. *If $X = X^{k,D}(S)$ defined above, then the filling constant $\text{Fill}(j)$ is $\leq C(D, k)S$.*

Plugging Proposition 2.7 into the Width-and-filling inequality (**), we see that the combinatorial width of $X^{k,D}(S)$ is at least $c(D, k)S^{D-k}$ as desired.

If X^k is the k -skeleton of a D -manifold with a polyhedral structure, then we can apply Poincare duality and relate $\text{Fill}(j)$ to a homological filling for $(D-j)$ -cycles in the manifold. Let Y denote the dual polyhedral structure. Then $\text{Fill}(j)$ can equivalently be defined as follows: $\text{Fill}(j)$ is the smallest number so that every boundary $a \in C_{D-j}(Y, \mathbb{Z}_2)$ has a filling $b \in C_{D-j+1}(Y, \mathbb{Z}_2)$ with $\partial b = a$ and $\text{Vol}(b) \leq \text{Fill}(j)\text{Vol}(a)$. Here $\text{Vol}(b)$ denotes the number of faces in the support of b . This kind of filling inequality is a combinatorial version of an isoperimetric inequality.

The complexes $X^{k,D}(S)$ are the k -skeleta of a polyhedral structure on the D -cube. The dual polyhedral structure, Y , is also a cubical grid. It has one vertex at the center of each D -cell in the original grid, and so on. A j -dimensional cocycle in $X^{j,D}(S)$ corresponds to a $(D-j)$ -dimensional relative cycle in Y .

So after applying Poincare duality, the filling constant bound $\text{Fill}(j) \leq C(D, k)S$ for $X^{k,D}(S)$ is equivalent to the following estimate.

Proposition 2.8. *Let Y denote a cubical grid in D -dimensional space with side length S . Suppose that a is a relative $(D-j)$ -cycle in the grid consisting of $|a|$ faces. Then a is the (relative) boundary of a $(D-j+1)$ -chain b in the grid consisting of $\leq c(D, k)S|a|$ faces.*

This proposition is a combinatorial version of the standard Federer-Fleming pushout argument. (See [Gu2] for the details of the standard argument.) The combinatorial version is an easy consequence of the standard pushout argument and the deformation theorem.

Proof. Let x be a random point (not necessarily a vertex) in the cube Y . We fill a by a geometric (but not cubical) chain by pushing out from the point x . This is defined in the following way. Let $C(a)$ denote the cone consisting of all the line segments from x to points on a . Let $C^+(a)$ denote the infinite cone, consisting of all the rays from x through a point of a . We can fill a by the relative chain given by $[C^+(a) - C(a)] \cap Y$.

By an averaging argument invented by Federer and Fleming, one sees that the average volume of this chain, as x varies in the cube Y , is bounded by $C(D, j)S|a|$. Let b_0 be one of these chains with at most average volume.

The chain b_0 is not a cubical chain. We finish the argument by approximating b_0 with a cubical chain b . The deformation theorem allows us to approximate b_0 by a cubical chain b so that $\partial b = \partial b_0 = a$, and with $\text{Vol}(b) \leq C(D, j)\text{Vol}(b_0)$.

This chain b obeys the conclusion of the proposition. \square

2.3. Open questions: triangulated manifolds. There are many open questions about the case of triangulated manifolds. Suppose X is a triangulated k -manifold with $\lesssim 1$ simplices containing any vertex and with N simplices total. If $n \geq 2k + 1$, then we can use the embedding construction from Section 2.1 to embed X with thickness 1 into $B^n(R)$ for $R \lesssim C_\epsilon N^{\frac{1}{n-k} + \epsilon}$. We don't know whether this is sharp.

The combinatorial width method used in Section 2.2 does not work directly for manifolds. In Section 2.9f of [Gr2], it is proven that the combinatorial width of a k -manifold X^k over \mathbb{R}^k is always $\leq 4k$. One may still get some estimates by considering lower-dimensional skeleta of the manifold. A thick embedding of X^k into \mathbb{R}^n restricts to a thick embedding of any skeleton of X^k .

Now we consider some examples.

Example 0. If $k = 1$, then a triangulated closed k -manifold is just a union of circles, each circle divided into some number of edges. If the total number of edges is N , then X^1 embeds with combinatorial thickness 1 into $B^n(R)$ for $R \sim N^{1/n}$ in any dimension $n \geq 2$. The case $k = 1$ is especially simple, but it may still suggest that manifolds are easier to embed than general complexes.

Example 1. Consider a family of arithmetic hyperbolic surfaces, Σ_i given as coverings of a surface Σ_0 . We let $G_i \rightarrow +\infty$ denote the genus of Σ_i . These surfaces have natural triangulations, given by picking a triangulation of Σ_0 and then lifting it to the Σ_i . What is the smallest radius so that the triangulated manifold Σ_i embeds into $B^n(R)$ with combinatorial thickness 1? Theorem 2.1 guarantees that such embedding exists with $R \sim G_i^{\frac{1}{n-2}}$ for $n \geq 5$.

On the other hand, the 1-skeleton of our triangulation of Σ_i is an expander graph with $\sim G_i$ vertices. The expander properties of arithmetic hyperbolic manifolds are discussed more in the appendix. An embedding of Σ_i with combinatorial thickness 1 restricts to give an embedding of the 1-skeleton with combinatorial thickness at least 1. Therefore, the radius R above must be $\gtrsim G_i^{\frac{1}{n-1}}$. Moreover, there is an actual embedding of the 1-skeleton into $B^n(R)$ with combinatorial thickness 1 and $R \sim G_i^{\frac{1}{n-1}}$ for $n \geq 3$. Can we extend this embedding to all of Σ_i ?

(One should remember here that the combinatorial thickness of an embedding $\Sigma_i \rightarrow \mathbb{R}^n$ depends on the choice of triangulation. Two different triangulations of the same surface can have very different properties. One may find other triangulations of a surface of genus G_i that embed with combinatorial thickness 1 into a ball $B^n(R)$ of radius $R \lesssim G_i^{1/n}$. In the next section, we will study the retraction thickness of embeddings $\Sigma \rightarrow \mathbb{R}^n$. The retraction thickness does not depend on a triangulation of Σ .)

Example 2. Let $k = 2j$. Begin with the j -dimensional skeleton of a D -dimensional lattice with grid size S : $X^{j,D}(S)$. We fix D large, and then send $S \rightarrow \infty$. This complex has $\sim S^D$ simplices. Embed this complex into \mathbb{R}^{k+1} . Take a small tubular neighborhood, and let X^k be the boundary of this neighborhood, which is a manifold. We can triangulate X^k so that $X^{j,D}(S)$ appears inside the j -skeleton of the triangulation, and also the triangulation has bounded local degree and $N \sim S^D$ simplices. By the lower bound in the last subsection, a 1-thick embedding of X^k into \mathbb{R}^n has 1-neighborhood with volume at least $N^{\frac{n}{n-j}}$.

If X^k is a simplicial complex, we define the combinatorially-thick embedding radius of X in \mathbb{R}^n to be the smallest R so that X embeds with combinatorial thickness 1 into $B^n(R)$.

Question 1. If X^k is a triangulated manifold with N simplices and each vertex in $\lesssim 1$ simplices, what can we say about the combinatorially-thick embedding radius of X^k ? Is any X^k significantly harder to embed than Example 2 above?

Question 2. If X^k is a triangulated manifold with N simplices and each vertex in $\lesssim 1$ simplices, what can we say about the combinatorial thickness of X^j over \mathbb{R}^j ? Here $1 \leq j \leq k$, and X^j denotes the j -skeleton of X .

If $1 \leq j \leq k/2$, then Example 2 shows that X^j may have combinatorial thickness $\gtrsim N^{1-\epsilon}$, which is nearly optimal. If $j = k$, then the result of Sec 2.9f of [Gr2] says that the combinatorial width is $\leq 4k$ regardless of N . For $k/2 < j < k$, the situation is unclear. This X^j may be the j -skeleton of a k -dimensional grid, and the results in Section 2.2 show that the combinatorial width of such X^j over \mathbb{R}^j is $\gtrsim N^{\frac{k-j}{k}}$.

Question 3. If X^k is a triangulated manifold with N simplices and each vertex in $\lesssim 1$ simplices, what can we say about the filling constants $Fill(j)$ of X^k ?

If $1 \leq j \leq k/2$, then Example 2 shows that $Fill(j)$ may be $\lesssim N^\epsilon$. On the other hand, for any complex $Fill(j) \gtrsim 1$, so this upper bound is nearly sharp. For $j > k/2$, the situation is unclear. The X^j may be the j -skeleton of a cubical grid of side length $N^{1/k}$. In this case, the results of Section 2.2 show that $Fill(j) \lesssim N^{1/k}$.

Also, if X is connected and $H^j(X, \mathbb{Z}_2) = 0$ for all $1 \leq j \leq k-1$, then the width-and-filling inequality cited in Section 2.2 applies. Since the combinatorial width of X over \mathbb{R}^k is only $4k$, we get the following estimate:

$$N \leq C(k) \prod_{j=1}^k Fill(j).$$

Finally, if X is a k -manifold, it embeds into \mathbb{R}^{2k} by the Whitney embedding theorem. It would be interesting to prove quantitative estimates for such an embedding.

3. ESTIMATES FOR RETRACTION THICKNESS

Suppose that X is a CW-complex embedded in \mathbb{R}^n . We say that the retraction thickness of X is at least T if the T -neighborhood of X retracts to X . In this section, we study how the retraction thickness relates to the topology of X . Suppose for example that X is embedded in \mathbb{R}^n with retraction thickness 1 and that the 1-neighborhood of X has volume V . Based on this information, what can we conclude about the topology of X ?

3.1. Constructing embeddings. The quantitative general position arguments from Section 2.1 can also be used to construct embeddings with controlled retraction thickness.

Theorem 3.1. *If X^k is a k -dimensional simplicial complex with N simplices and each vertex lies in $\leq L$ simplices, and if $n \geq 2k + 1$, then there is an embedding with retraction thickness 1 from X into $B^n(R)$ for $R \leq C(n, L, \epsilon) N^{\frac{1}{n-k} + \epsilon}$.*

The proof of Theorem 3.1 is a technical modification of the proof of Theorem 2.1. We give the proof in Section 3.4.

For combinatorial thickness, Theorem 2.1 is extremely sharp. But we don't know how sharp Theorem 3.1 is. When $k = 1$, we will see that Theorem 3.1 is far from sharp. We don't know what happens when $k \geq 2$.

When we first defined retraction thickness, we expected it to be a minor variation of the combinatorial thickness discussed in Section 2. But it turns out to be quite different. For example, an expander with N vertices embeds with combinatorial thickness 1 into $B^3(R)$ only for $R \gtrsim N^{1/2}$, but it embeds with retraction thickness 1 into $B^3(R)$ for $R \sim N^{1/3}$. From the point of view of combinatorial thickness, an expander is much more complicated than a grid (with the same number of vertices). But from the point of view of retraction thickness, an expander and a grid are basically equivalent. The underlying reason is that an expander is homotopy equivalent to a grid with roughly the same number of vertices. The significance of homotopy equivalence appears in the following proposition.

Proposition 3.1. *Let X^k and Y^k be homotopy equivalent CW-complexes of dimension k . Suppose that $n \geq 2k + 1$, and suppose that Y embeds into \mathbb{R}^n with retraction thickness T . Then X embeds into \mathbb{R}^n with retraction thickness at least $T - \epsilon$ for any $\epsilon > 0$.*

Proof. We consider Y as a subset of \mathbb{R}^n . Let $\Psi : X \rightarrow Y$ be a homotopy equivalence. We can think of Ψ as a map $X \rightarrow \mathbb{R}^n$. Now Ψ may not be an embedding, but since $n \geq 2k + 1$, we can perturb Ψ slightly to an embedding Ψ' . Since the perturbation is slight, we may arrange that the $(T - \epsilon)$ -neighborhood of $\Psi'(X)$ lies inside of the T -neighborhood of Y .

We know that there is a retraction R from the T -neighborhood of Y to Y . Since Ψ is a homotopy equivalence, we also know that there is a map $\Phi : Y \rightarrow X$ so that $\Phi \circ \Psi : X \rightarrow X$ is homotopic to the identity. We consider the map $\Phi \circ R$ which goes from the $(T - \epsilon)$ -neighborhood of $\Psi'(X)$ to X . We claim that this map is a homotopy retraction. In other words, when we restrict the map to $X = \Psi'(X)$, we get a map homotopic to the identity. To see this, notice that Ψ' is homotopic to Ψ inside the $(T - \epsilon)$ neighborhood. So the restriction of our map to X is homotopic to $\Phi \circ R \circ \Psi$. But Ψ maps X into Y , and R is the identity on Y , so $\Phi \circ R \circ \Psi$ is equal to $\Phi \circ \Psi$ which is homotopic to the identity.

We have now proven that the $(T-\epsilon)$ -neighborhood of $\Psi'(X)$ homotopy retracts to $\Psi'(X)$ by the map $\Phi \circ R$. If we restrict this map to $\Psi'(X)$, then it is homotopic to the identity. By the homotopy extension theorem, we can extend this homotopy to get a retraction from the $(T-\epsilon)$ -neighborhood of $\Psi'(X)$ to $\Psi'(X)$. In other words, X is embedded in \mathbb{R}^n with retraction thickness at least $T-\epsilon$. \square

We pause here to recall some results we use about homotopy retractions and the homotopy extension property. First, we recall the definition of a homotopy retraction. If $A \subset B$, then a map $F : B \rightarrow A$ is a homotopy retraction if the restriction $F : A \rightarrow A$ is homotopic to the identity. A retraction is of course a special case of a homotopy retraction. On the other hand, if A is a finite simplicial complex or CW complex topologically embedded in \mathbb{R}^n , and B is a neighborhood of A , then the pair (B, A) has the homotopy extension property. This means that if $g : B \rightarrow Y$ is a continuous map to any space Y , and $h : A \times [0, 1] \rightarrow Y$ is a homotopy with $h(a, 0) = g(a)$ for all $a \in A$, then the homotopy h can be extended to $G : B \times [0, 1] \rightarrow Y$ with $G(b, 0) = g(b)$ for all $b \in B$. (See for example sections 2.9-2.10 in [NR].) In particular, any homotopy retraction $B \rightarrow A$ may be homotoped to a genuine retraction $B \rightarrow A$. When we have to construct a retraction, it can be easier to first construct a homotopy retraction and then use this method to move it to a real retraction. We did this in the proof of Proposition 3.1, and we will do it again when we prove Theorem 3.1 in Section 3.4. The theorem about the homotopy extension property cited above has a fairly short proof, but we could also avoid using it by talking throughout about homotopy retractions and “homotopy retraction thickness”. Everything we prove about retraction thickness below applies just as well with homotopy retractions in place of retractions.

As a corollary of Proposition 3.1, we see that expanders embed with retraction thickness 1 into rather small balls.

Proposition 3.2. *Let Γ be any graph with degree $\lesssim 1$ and N vertices. Then Γ may be embedded with retraction thickness 1 into $B^3(R)$ for $R \lesssim N^{1/3}$.*

Proof. It’s straightforward to reduce to the case that Γ is connected. If Γ is connected, then it is homotopy equivalent to any other graph with the same rank of H^1 . In particular, Γ is homotopy equivalent to a subgraph of a grid with $\lesssim N$ vertices. As we saw in Section 1, such a grid can be embedded with combinatorial thickness 2 into a ball of radius $\lesssim N^{1/3}$. It’s straightforward to check that the embedding we constructed in Section 1 also has retraction thickness at least 2. By Proposition 3.1, we get an embedding of Γ with retraction thickness 1 into a ball of radius $\sim R^{1/3}$. \square

Proposition 3.2 turns out to be sharp, as we will see in the next section.

3.2. Estimates for rank of homology and simplicial volume. Suppose that X is a CW-complex embedded in \mathbb{R}^n with retraction thickness T . Let V denote the volume of the T -neighborhood of X . Then VT^{-n} is a scale-invariant quantity that describes the geometric complexity of the embedding. As we will see, this geometrical complexity

controls some aspects of the homotopical complexity of X . In this subsection, we show that VT^{-n} controls the homology groups of X and the simplicial volume of X .

Proposition 3.3. *Suppose X is a CW-complex embedded in \mathbb{R}^n with retraction thickness T . Let V be the volume of the T -neighborhood of X . Then the following inequality holds.*

$$\text{Rank}H_*(X) \lesssim VT^{-n}.$$

Proof. We write $N_W(X)$ to denote the W -neighborhood of X .

Let p_1, p_2, \dots be a maximal set of $T/2$ -separated points in $N_{T/2}(X)$. The balls $B(p_i, T/2)$ cover $N_{T/2}(X)$. Since the balls $B(p_i, T/4)$ are disjoint and lie within $N_T(X)$, we see that the number of points is $\lesssim VT^{-n}$. We let $U := \cup_i B(p_i, T/2)$. Since $X \subset U \subset N_T(X)$, we see that U retracts to X .

The balls $B(p_i, T/2)$ give an open cover of U , and we let N denote the nerve of this cover. We have a natural map to the nerve $\Phi : U \rightarrow N$. Since the intersection of any set of balls is convex and hence contractible, the map Φ is a homotopy equivalence of U and N .

With this setup, we show that the identity map from X to X factors through N up to homotopy. We can map X to N by restricting Φ to X . Now Φ has a homotopy inverse $\Psi : N \rightarrow U$. We let R denote the retraction from U to X . Now $\Psi \circ \Phi : U \rightarrow U$ is homotopic to the identity. Therefore, $R \circ \Psi \circ \Phi : X \rightarrow X$ is also homotopic to the identity.

As a consequence, $\text{Rank}H_*(X) \leq \text{Rank}H_*(N)$.

Our cover of U involves $\lesssim VT^{-n}$ balls $B(p_i, T/2)$. Since the balls $B(p_i, T/4)$ are disjoint, the multiplicity of the cover is $\lesssim 1$. Therefore the nerve N contains at most $\lesssim VT^{-n}$ simplices. Therefore, $\text{Rank}H_*(N) \lesssim VT^{-n}$. □

In particular, if Γ is a grid or expander with N vertices then $\text{Rank}H_1(\Gamma) \sim N$. So if Γ embeds with retraction thickness 1 into $B^3(R)$, we see that $R \gtrsim N^{1/3}$. So we see that Proposition 3.2 is sharp.

The next proposition concerns simplicial norms modulo p . If a lies in \mathbb{Z}_p (the integers modulo p), we define $|a|$ to be zero if $a = 0$ and one if $a \neq 0$. If $h \in H_k(X, \mathbb{Z}_p)$, we define the simplicial norm of h to be the infimum of $\sum |a_j|$ over all cycles $\sum_j a_j f_j$ which represent h . (In this formula, the f_j denote maps from the k -simplex to X and $a_j \in \mathbb{Z}_p$.) We denote the simplicial norm of h by $\|h\|_\Delta$. Simplicial norms over \mathbb{R} are better known, but simplicial norms over \mathbb{Z}_p share some of their good properties. In particular, the simplex straightening argument shows that for a complete hyperbolic manifold (M, hyp) , for any $h \in H_k(M, \mathbb{Z}_p)$ with $k \geq 2$, we have $\|h\|_\Delta \gtrsim \text{mass}(h)$. In particular, if M is closed, the simplicial norm of the fundamental class $[M]$ is $\gtrsim \text{Vol}(M, \text{hyp})$. (See [MT] and the appendix.)

Proposition 3.4. *Suppose X is a CW-complex embedded in \mathbb{R}^n with retraction thickness T . Let V be the volume of the T -neighborhood of X . Let $h \in H_k(X, \mathbb{Z}_p)$ be any homology class. Then the following inequality holds.*

$$\|h\|_\Delta \lesssim VT^{-n}.$$

Proof. As in the proof of Proposition 3.3, we define the nerve N and the map $\Phi : X \rightarrow N$. As we saw in the proof of Proposition 3.3, the identity map from X to itself factors through the map $\Phi : X \rightarrow N$, up to homotopy.

If $F : X \rightarrow Y$ is any continuous map, and h is any homology class in $H_k(X, \mathbb{Z}_p)$, it follows from the definition of simplicial norm that $\|F_*(h)\|_\Delta \leq \|h\|_\Delta$. Since the identity map factors through Φ , it follows that $\|\Phi(h)\|_\Delta = \|h\|_\Delta$.

But we can represent $\Phi(h)$ by a sum $\sum a_j \Delta_j$ where $a_j \in \mathbb{Z}_p$ and Δ_j are simplices of the nerve N . Hence $\|h\|_\Delta = \|\Phi(h)\|_\Delta$ is at most the number of simplices in N . As we saw in the proof of Proposition 3.3, the number of simplices in N is $\lesssim VT^{-N}$. \square

(Here are some further questions about bounding the homotopical complexity of X in terms of VT^{-n} . Can we bound the torsion in $H_*(X, \mathbb{Z})$ in terms of VT^{-n} ? For example, if X_D is the CW complex $S^d \cup_f B^{d+1}$, where the attaching map $f : S^d \rightarrow S^d$ has degree D , and X_D is embedded in \mathbb{R}^n , how small can VT^{-n} be? Also, can we bound the real simplicial volume of X in terms of VT^{-n} ?)

To finish Section 3.2, we apply these propositions to some examples. We get good estimates for the retraction thickness for k -skeleta of grids, for 2-dimensional manifolds, and for some 3-dimensional manifolds.

Example 1. Let $X^{k,D}(S)$ denote the k -skeleton of a D -dimensional grid of side length S . We fix k, D and consider asymptotics as $S \rightarrow \infty$. For this example, the retraction thickness behaves very differently from the combinatorial thickness. We let N denote the number of simplices in $X^{k,D}(S)$. If $X^{k,D}(S)$ is embedded with combinatorial thickness 1 into $B^n(R)$, then we showed in Section 2.2 that $R \gtrsim N^{\frac{1}{n-k} \frac{D-k}{D}} \sim N^{\frac{1}{n-k} - \epsilon}$. But for any $n \geq 2k+1$, we will embed $X^{k,D}(S)$ with retraction thickness 1 into $B^n(R)$ for $R \sim N^{1/n}$.

To construct the embedding, let Y be the k -skeleton of an n -dimensional grid which is homotopy equivalent to X . Such a Y has $\sim N$ cells, and it comes embedded with retraction thickness $\gtrsim 1$ into a ball $B^n(R)$ with $R \sim N^{1/n}$. Since X and Y are homotopy equivalent and $n \geq 2k+1$, Proposition 3.1 implies that X embeds into the same $B^n(R)$ with retraction thickness $\gtrsim 1$.

This construction is basically sharp. The complex $X^{k,D}(S)$ has $N \sim S^D$ cells, and $H^k(X)$ has rank $\sim S^D \sim N$. By Proposition 3.3, if X embeds with retraction thickness 1 into $B^n(R)$, then $R \gtrsim N^{1/n}$.

Example 2. Let Σ be a closed surface of genus g . For each $n \geq 3$, it's straightforward to embed Σ with retraction thickness 2 into an n -dimensional cylinder with radius 10 and length $10g$: $B^{n-1}(10) \times [0, 10g]$. This cylinder C -bilipschitz embeds into $B^n(R)$ for $R \sim g^{1/n}$. Hence Σ embeds with retraction thickness 1 into $B^n(R)$ for $R \sim g^{1/n}$. Since $H_1(\Sigma)$ has rank $2g$, this radius cannot be improved.

Example 3. Let X be a closed k -dimensional hyperbolic manifold with volume V . In particular, the simplicial volume of X is $\gtrsim V$. Therefore, if X is embedded with retraction

thickness 1 into \mathbb{R}^n , then the 1-neighborhood of X has volume $\gtrsim V$. If X is embedded with retraction thickness 1 into $B^n(R)$, then $R \gtrsim V^{1/n}$.

This estimate is sharp for cyclic coverings. Suppose that X_1 is a closed hyperbolic k -manifold and that there is a surjective homomorphism $\pi_1(X_1) \rightarrow \mathbb{Z}$. Then we can construct corresponding cyclic coverings $X_D \rightarrow X_1$ of degree D . The hyperbolic volume of X_D is $\sim D$. If $n \geq 2k + 1$, then this X_D can be embedded with retraction thickness 1 into a solid torus $S^1(L) \times B^{n-1}(r)$ with radius $r \lesssim 1$ and $L \sim D$. This solid torus in turn admits a C -bilipschitz embedding into $B^n(R)$ for $R \sim D^{1/n}$. Hence X_D can be embedded with retraction thickness 1 into $B^n(R)$ for $R \sim D^{1/n}$.

3.3. Retraction thickness for arithmetic hyperbolic manifolds. We will prove a stronger bound on the retraction thickness for arithmetic hyperbolic manifolds of dimension $k \geq 3$. In the appendix, we give a review of arithmetic hyperbolic manifolds. Here, we quickly mention the facts we need for our argument. In each dimension $k \geq 2$, arithmetic covers can be used to construct a sequence of closed hyperbolic manifolds X_i with volume $V_{hyp}(X_i) \rightarrow +\infty$, and with uniformly bounded Cheeger isoperimetric constant $h(X_i) \geq c > 0$ for all i . Moreover, each X_i may be triangulated with $N_i \sim V_{hyp}(X_i)$ simplices. The following theorem shows that it is difficult to embed such arithmetic manifolds into \mathbb{R}^n with a given retraction thickness.

Theorem 3.2. *Suppose that X^k is a closed hyperbolic manifold with volume V_{hyp} and Cheeger isoperimetric constant h , with dimension $k \geq 3$. If X is embedded in \mathbb{R}^n with retraction thickness T , and the T -neighborhood of X in \mathbb{R}^n has volume V , then the following inequality holds.*

$$h^{\frac{n}{n-1}} V_{hyp}^{\frac{n}{n-1}} \lesssim VT^{-n}.$$

Before turning to the proof, we make some comments about the theorem. The most interesting case is when X is an arithmetic hyperbolic manifold described above. Such a manifold X can be triangulated with N simplices, and has $V_{hyp} \sim N$ and $h \sim 1$. Therefore, if X is embedded into \mathbb{R}^n with retraction thickness 1, the 1-neighborhood of X has volume $\gtrsim N^{\frac{n}{n-1}}$. This estimate is significantly stronger than what we get by applying the estimate for $\text{Rank}H_*(X)$ in Proposition 3.3 or the estimate for simplicial volume in Proposition 3.4. Since X is triangulated with N simplices, $\text{Rank}H_*(X) \lesssim N$ and the simplicial norm of X is $\leq N$. Using the rank of $H_*(X)$ and the simplicial norms of X , we can only prove that the volume of the 1-neighborhood of X is $\gtrsim N$. The moral of Theorem 3.2 is that the hyperbolic manifolds with Cheeger constant ~ 1 are more topologically complicated than other hyperbolic manifolds of the same volume (such as cyclic coverings).

On the other hand, there is a significant gap between the bounds in Theorem 3.1 and Theorem 3.2. For example, consider embedding a 3-dimensional arithmetic hyperbolic manifold X^3 into $B^7(R)$. What is the smallest R so that X^3 embeds in $B^7(R)$ with retraction thickness 1? Theorem 3.1 says that this radius is $\lesssim N^{1/4+\epsilon}$. Theorem 3.2 says that this radius is $\gtrsim N^{1/6}$.

Theorem 3.2 is somewhat analogous to the theorem about combinatorial thickness of expander graphs. To see the analogy, let us look at the case $k = 3$, and consider an arithmetic hyperbolic 3-manifold X^3 . A key fact about expander graphs is that any map from an expander graph to \mathbb{R} has a “complicated” level set which intersects many edges. The key fact about arithmetic hyperbolic 3-manifolds is that any map from X^3 to \mathbb{R} has a “complicated” level set which is a surface of large genus. See the appendix for more information, and some history of this fact.

Using this key fact, we may sketch the main point of our proof. Suppose that X is an arithmetic hyperbolic 3-manifold triangulated with N simplices embedded into \mathbb{R}^n with retraction thickness 1, and let V denote the volume of $N_1(X)$, the 1-neighborhood of X . By the Falconer slicing theorem, we may slice \mathbb{R}^n by parallel hyperplanes so that each hyperplane intersects $N_1(X)$ in surface area $\lesssim V^{\frac{n-1}{n}}$. (The Falconer slicing estimate is recalled in Section 1.1.) By the key fact in the last paragraph, one of the hyperplanes intersects X in a surface Σ of genus $\gtrsim N$. Let us call this hyperplane P . We know that Σ has genus $\gtrsim N$ and we know that the 1-neighborhood of Σ in P has volume $\lesssim V^{\frac{n-1}{n}}$. Suppose for a second that we knew that the retraction thickness of Σ in P was ≥ 1 . Then Proposition 3.3 would imply that $N \lesssim V^{\frac{n-1}{n}}$ - the estimate we would like to prove. Morally, we think that this is the main idea of the proof. But strictly speaking, the 1-neighborhood of Σ may not retract to Σ - it only needs to retract into X . In the proof below we get around this technical difficulty by working with the nerve of a covering by balls, and by keeping track of many slices and how they fit together.

Proof of Theorem 3.2. By scaling, we may assume that $T = 1$.

We let $N_W(X) \subset \mathbb{R}^n$ denote the W -neighborhood of $X \subset \mathbb{R}^n$. Choose a maximal $1/4$ -separated set of points in $N_{1/2}(X)$: p_1, p_2, \dots . Let U be the open set $U := \cup_i B(p_i, 1/4)$. We have $X \subset N_{1/2}(X) \subset U \subset N_{3/4}(X)$. In particular, U retracts to X .

Our set U is covered by balls $U := \cup_i B(p_i, 1/4)$. We let N denote the nerve of this cover. Since an intersection of balls is convex and hence contractible, the nerve N is homotopy equivalent to the cover U . We let $\Phi : U \rightarrow N$ denote a map subordinate to the cover, and we let $\Psi : N \rightarrow U$ be a homotopy inverse of Φ . (In particular, $\Psi \circ \Phi : U \rightarrow U$ is homotopic to the identity.)

Next we apply the Falconer slicing inequality to the set $N_1(X)$ which has volume V . (The Falconer slicing inequality is recalled in Section 1.) According to the slicing inequality, we can rotate our coordinate frame so that for every $t \in \mathbb{R}$, the $(n-1)$ -dimensional volume of the “slice” $N_1(X) \cap \{x_n = t\}$ is $\lesssim V^{\frac{n-1}{n}}$.

The first key step in our proof is to understand how this slicing estimate interacts with the geometry of the nerve N . In order to do that, we intersect our manifold X with slabs $Slab(j) := \{j \leq x_n \leq j+1\}$.

Let $X_j := X \cap Slab(j)$. We view X_j and X as mod 2 chains, and observe that $X = \sum_j X_j$. (Since X is a closed manifold, all but finitely many X_j are empty - hence the sum $\sum_j X_j$ is a finite sum.)

The manifold X is closed, and so it is a mod 2 cycle. But the chains X_j may have boundary. Since we are working mod 2, $\partial X_j = X \cap \{x_n = j\} + X \cap \{x_n = j+1\}$. We define Z_j to be the mod 2 $(k-1)$ -cycle $X \cap \{x_n = j\}$. So $\partial X_j = Z_j + Z_{j+1}$. Each Z_j is a cycle in X . And each Z_j is null-homologous because it bounds $X \cap \{x_n \geq j\}$.

Similarly, we divide the nerve N according to the slabs $Slab(j)$. To begin with, we let \mathfrak{B} denote our set of balls $\{B(p_i, 1/4)\}$. Next, we let \mathfrak{B}_j denote the set of balls in \mathfrak{B} which intersect $Slab(j)$. We define N_j to be nerve corresponding to the set of balls \mathfrak{B}_j . In other words, $N_j \subset N$, and a simplex of N lies in N_j if and only if all of the balls corresponding to the vertices of the simplex intersect $Slab(j)$.

Our geometric estimate about the surface area of slices $N_1(X) \cap \{x_n = t\}$ allows us to control the number of simplices in each N_j .

Lemma 3.5. *For each j , the number of simplices in N_j is $\lesssim V^{\frac{n-1}{n}}$.*

Proof. By a standard argument, we prove that each point $x \in \mathbb{R}^n$ lies in $\lesssim 1$ balls of \mathfrak{B} . Since the centers p_i are $1/4$ -separated, the balls $B(p_i, 1/8)$ are disjoint. If a point x lies in $B(p_i, 1/4)$, then $B(p_i, 1/8)$ lies in $B(x, 3/8)$. There are $\lesssim 1$ disjoint balls of radius $1/8$ in any ball of radius $3/8$, and this proves the estimate.

In particular, any point x lies in $\lesssim 1$ balls of \mathfrak{B}_j . So to prove the lemma, it suffices to prove that there are $\lesssim V^{\frac{n-1}{n}}$ balls in \mathfrak{B}_j .

To do this, we consider the doubles of the balls in \mathfrak{B} : the set $B(p_i, 1/2)$. We let $U' := \cup_i B(p_i, 1/2) \subset N_1(X)$. If $B(p_i, 1/4)$ lies in \mathfrak{B}_j , then $B(p_i, 1/2) \cap Slab(j)$ has volume $\gtrsim 1$. The balls $B(p_i, 1/2)$ also have multiplicity $\lesssim 1$, and so the number of balls in \mathfrak{B}_j is bounded $\lesssim Vol_n[U' \cap Slab(j)]$.

This last volume is bounded above in terms of slices:

$$Vol_n[U' \cap Slab(j)] \leq \int_j^{j+1} Vol_{n-1}[N_1(X) \cap \{x_n = t\}] dt \lesssim V^{\frac{n-1}{n}}.$$

This finishes the proof of the lemma. \square

Since the map Φ is subordinate to the cover of U by the balls of \mathfrak{B} , Φ maps each X_j into N_j . Also, Φ maps Z_j into N_j .

Next we deform Φ to a map Φ' which takes each X_j into the k -skeleton of N_j and each Z_j into the $(k-1)$ -skeleton of N_j . We define X'_j to be the mod 2 k -chain given by $\Phi'(X_j)$ and we define Z'_j to be the mod 2 $(k-1)$ -cycle given by $\Phi'(Z_j)$. Because Z_j was null-homologous in X , Z'_j is null-homologous in N . Because of our bounds on the geometry of N , we know that each X'_j and each Z'_j has $\lesssim V^{\frac{n-1}{n}}$ simplices.

Next we move our information about chains and cycles in the nerve N back to information about chains and cycles in X .

Recall that the nerve N is homotopy equivalent to U . We have a map $\Psi : N \rightarrow U$ and $\Psi \circ \Phi$ is homotopic to the identity. Since Φ is homotopic to Φ' , $\Psi \circ \Phi' : U \rightarrow U$ is also homotopic to the identity.

Now U retracts to X . Let $R : U \rightarrow X$ be the retraction. So we see that $R \circ \Psi \circ \Phi' : X \rightarrow X$ is homotopic to the identity. In particular, $R \circ \Psi \circ \Phi'([X])$ is homologous to $[X]$. Therefore, we can decompose the cycle $[X]$ in the following way:

$$[\sum_j R \circ \Psi(X'_j)] = [X]. \quad (1)$$

To exploit our information about the hyperbolic metric on X , we use the simplex straightening method developed by Thurston and Milnor in the 1970's [MT].

Simplex straightening lemma. ([MT]) *If N denotes any simplicial complex and X is a complete hyperbolic manifold, and $F : N \rightarrow X$ is a continuous map, then F may be homotoped to a “straight map” $S : N \rightarrow X$ which maps each d -simplex of N to a geodesic d -simplex in X . In particular, for $d \geq 2$ the image $S(\Delta^d)$ has d -volume $\lesssim 1$ for each simplex $\Delta^d \subset N$.*

In our case, we have a map $R \circ \Psi$ from N to X , and we homotope it to a straight map S . Applying this homotopy to equation (1), we get

$$[\sum_j S(X'_j)] = [X]. \quad (2)$$

We let $\bar{X}_j := S(X'_j)$, and we let $\bar{Z}_j = S(Z'_j)$. The geometric properties of the straightening map allow us to bound the volumes of \bar{X}_j and \bar{Z}_j . Because X'_j consists of $\lesssim V^{\frac{n-1}{n}}$ simplices, the k -volume of \bar{X}_j is $\lesssim V^{\frac{n-1}{n}}$. Because $k \geq 3$ and Z'_j consists of $\lesssim V^{\frac{n-1}{n}}$ simplices, the $(k-1)$ -volume of \bar{Z}_j is $\lesssim V^{\frac{n-1}{n}}$.

By equation (2), $\sum \bar{X}_j$ is homologous to X . Since $\partial X'_j = Z'_j + Z'_{j+1}$, we see that $\partial \bar{X}_j = \bar{Z}_j + \bar{Z}_{j+1}$. Since Z'_j are null-homologous in N , \bar{Z}_j is null-homologous in X .

At this point we can use the isoperimetric information about X^k . Recall that h is the Cheeger isoperimetric constant of X^k with its hyperbolic metric. This means that if $U \subset X$ is an open set with volume $\leq (1/2)V_{hyp}$, then the surface area of ∂U is $\geq h \text{Vol}(U)$. Based on this definition, it follows that any null-homologous mod 2 $(k-1)$ -cycle Z in X^k bounds a k -chain Y with $\text{Vol}_k(Y) \leq h^{-1} \text{Vol}_{k-1}(Z)$. Since each of our cycles \bar{Z}_j is null-homologous, we can find a k -chain \bar{Y}_j with $\partial \bar{Y}_j = \bar{Z}_j$ obeying the volume estimate $\text{Vol}_k(\bar{Y}_j) \lesssim h^{-1} \text{Vol}_{k-1}(\bar{Z}_j) \lesssim h^{-1} V^{\frac{n-1}{n}}$.

Now we can decompose the fundamental class of X as a sum of cycles:

$$[X] \sim \sum_j (\bar{X}_j + \bar{Y}_j + \bar{Y}_{j+1}).$$

When we sum over j , each \bar{Y}_j appears twice and cancels. Hence the right-hand side is equal to $\sum_j \bar{X}_j$ which is indeed homologous to $[X]$.

On the other hand, each term $\bar{X}_j + \bar{Y}_j + \bar{Y}_{j+1}$ is a cycle because its boundary is $\bar{Z}_j + \bar{Z}_{j+1} + \bar{Z}_j + \bar{Z}_{j+1}$ and we are working modulo 2. So one of the cycles $(\bar{X}_j + \bar{Y}_j + \bar{Y}_{j+1})$ has

volume at least V_{hyp} . Comparing this lower bound with our upper bounds for the volumes of \bar{X}_j and \bar{Y}_j , we see

$$V_{hyp} \lesssim (1 + h^{-1})V^{\frac{n-1}{n}}.$$

Finally, we note that any closed hyperbolic manifold has $h \lesssim 1$, and so the h^{-1} dominates the 1.

$$V_{hyp} \lesssim h^{-1}V^{\frac{n-1}{n}}.$$

□

Possible generalizations. Theorem 3.2 can probably be generalized to many non-hyperbolic manifolds as well. We used hyperbolicity only to apply simplex-straightening and to bound the volumes of straight simplices of dimension k and $k - 1$. For example, if X^k is a locally symmetric space with negative Ricci curvature, then it is possible to apply simplex straightening, and the volume of a k -dimensional straight simplex was bounded by Lafont and Schmidt in [LS]. To apply the proof above, one also needs a bound on the volumes of straight simplices of dimension $k - 1$. If the universal cover of X has a hyperbolic plane as a factor, then the volumes of straight simplices of dimension $k - 1$ will be unbounded. But if the universal cover of X does not have a hyperbolic plane as a factor, then it may be possible to prove such a bound along the lines of [LS].

3.4. Strong combinatorial thickness and retractions. In this section, we give the proof of Theorem 3.1.

Theorem 3.1. *If X^k is a k -dimensional simplicial complex with N simplices and each vertex lies in $\leq L$ simplices, and if $n \geq 2k + 1$, then there is an embedding with retraction thickness 1 from X into $B^n(R)$ for $R \leq C(n, L, \epsilon)N^{\frac{1}{n-k} + \epsilon}$.*

We adapt the proof of Theorem 2.1. In order to control retraction thickness, we need the following variation of combinatorial thickness.

If X is a k -dimensional simplicial complex, we say that a topological embedding $I : X \rightarrow \mathbb{R}^n$ has strong combinatorial thickness $\geq T$ if the following holds. Given any simplices $\Delta_1, \dots, \Delta_J$ of X , then $\cap_{j=1}^J N_T[I(\Delta_j)]$ is non-empty only if the simplices $\Delta_1, \dots, \Delta_J$ have a common vertex. (In other words, if and only if $\cap_{j=1}^J \Delta_j$ is non-empty.)

For example, suppose X is a triangle - a 1-complex with three edges, E_1, E_2, E_3 . If $I : X \rightarrow \mathbb{R}^3$ has combinatorial thickness at least 1, then it means that each vertex is not mapped too close to the opposite edge. If I has strong combinatorial thickness at least 1, then it means in addition that there is no point that lies too close to all three edges. The strong combinatorial thickness is related to retractions by the following proposition.

Proposition 3.6. *If $I : X \rightarrow \mathbb{R}^n$ is an embedding with strong combinatorial thickness at least T , then the $T - \epsilon$ neighborhood of $I(X)$ retracts to $I(X)$.*

Proof. In this proof, we will slightly abuse notation by identifying $I(X)$ and X . When we write $N_T(X)$, this means the T -neighborhood of X in \mathbb{R}^n .

Pick a fine triangulation of $N_{T-\epsilon}(X)$, where each edge of the triangulation has length $< \epsilon$. We first construct a map Ψ from $N_{T-\epsilon}(X)$ to X , building it one skeleton at a time. Next we will check that the restriction of Ψ to X is homotopic to the identity. In other words, Ψ is a homotopy retraction of $N_{T-\epsilon}(X)$ onto X . But since I is an embedding, the homotopy extension theorem allows us to homotope Ψ to a genuine retraction from $N_{T-\epsilon}(X)$ onto X .

We have to be careful with notation because X is a simplicial complex, and we need to talk about its simplices, and we also triangulated $N_{T-\epsilon}(X)$ and we need to think about the simplices of the triangulation. We use Δ^j to refer to a j -dimensional simplex of X . We use English letters to refer to simplices of the triangulation of $N_{T-\epsilon}(X)$: we call the vertices v and the higher-dimensional faces F .

We first define Ψ on the vertices of our triangulation of $N_{T-\epsilon}(X)$. For any vertex v , consider all the simplices $\Delta \subset X$ so that $v \in N_T[\Delta]$. By the definition of strong combinatorial thickness, *all of these simplices have a common vertex*. We define $\Psi(v)$ to be one of the common vertices.

Now we claim that Ψ extends to a simplicial map from $N_{T-\epsilon}(X)$ to X . Let F denote a d -simplex of $N_{T-\epsilon}(X)$ with vertices v_1, \dots, v_{d+1} . We have to check that $\Psi(v_1), \dots, \Psi(v_{d+1})$ are all vertices of a single simplex of X . By hypothesis, $v_1 \in N_{T-\epsilon}(X)$, and so there is a simplex $\Delta \subset X$ with $v_1 \in N_{T-\epsilon}(\Delta)$. Since the edges of the triangulation of $N_{T-\epsilon}(X)$ have length $< \epsilon$, all the vertices v_i lie in $N_T(\Delta)$. Now by our choice of $\Psi(v_i)$, we see that each $\Psi(v_i)$ lies in Δ . Hence Ψ extends to a simplicial map.

Next we have to check that Ψ is homotopic to the identity. To do this, we check that for each simplex $\Delta^j \subset X$, $\Psi(\Delta^j)$ lies in the closure of Δ^j . Let p be a point of some simplex $\Delta^j \subset X \subset \mathbb{R}^n$. The point p lies in some simplex F of our fine triangulation of $N_{T-\epsilon}(X)$. We let v_1, \dots, v_{d+1} denote the vertices of F . Because we chose a fine triangulation, we can assume that the distance from p to any v_i is $\leq \epsilon$. In particular, each v_i easily lies in $N_T(\Delta^j)$. Therefore $\Psi(v_i)$ is one of the vertices of Δ , and $\Psi(F)$ lies in the closure of Δ^j . In particular $\Psi(p)$ lies in the closure of Δ^j . Since p was an arbitrary point of Δ^j , $\Psi(\Delta^j)$ lies in the closure of Δ^j .

Therefore, Ψ restricted to X is homotopic to the identity. By the homotopy extension property, Ψ is homotopic to a retraction. \square

If an embedding $I : X \rightarrow \mathbb{R}^n$ has strong combinatorial thickness $> T$, then it has retraction thickness $> T$ also. Therefore, Theorem 3.1 follows from the following proposition.

Proposition 3.7. *Suppose that X is a k -dimensional simplicial complex with N simplices and that each vertex of X lies in $\leq L$ simplices. If $n \geq 2k+1$, then there is an embedding $I : X \rightarrow B^n(R)$ with strong combinatorial thickness > 1 , where $R \leq C(n, L)N^{\frac{1}{n-k}}(\text{polylog}N)$. In particular, the 1-neighborhood of $I(X)$ retracts to $I(X)$.*

This proposition is a modification of Theorem 2.1. We control the strong combinatorial thickness instead of the combinatorial thickness. On the other hand, the estimate is a little worse, with a $\text{polylog}N$ error factor in place of $(\log N)^{2k+2}$. If one follows the proof, the

power in the $\text{polylog} N$ turns out to be $\sim (\log N)^{Ck^4}$. The proof occupies the rest of Section 3.4.

This proof is a modification of the proof of Theorem 2.1 in Section 2.1. The proof begins in the same way. We let I_0 be a random facewise-linear embedding of X into $B^n(N^{\frac{1}{n-k}})$. We know that each unit ball $B^n(p, 1)$ intersects $\lesssim \log N$ simplices of $I_0(X)$. Next we subdivide X into a finer complex X' , so that each simplex of X' has diameter $\lesssim 1$. Then we perturb the map I_0 to a map $I : X' \rightarrow B^n$ by moving each vertex a distance ≤ 1 . After the perturbation, we need to check that the strong combinatorial thickness of $I : X' \rightarrow \mathbb{R}^n$ is $\geq \epsilon$ for some $\epsilon \gtrsim (\text{polylog} N)^{-1}$.

For any set of simplices $\Delta_1, \dots, \Delta_J \subset X'$, we say that $\Delta_1, \dots, \Delta_J$ have a common vertex if one vertex lies in all of the simplices. For any set of simplices $\Delta_1, \dots, \Delta_J$ with no common vertex, we define $\text{Bad}_\epsilon(\Delta_1, \dots, \Delta_J)$ to be the set of choices of I so that $\cap_{j=1}^J N_\epsilon[I(\Delta_j)]$ is non-empty. The map I has strong combinatorial thickness at least ϵ unless it lies in one of the sets Bad_ϵ .

For the original combinatorial thickness, the bad sets only involve two simplices. The new difficulty of strong combinatorial thickness is that the bad sets involve more simplices. However, we can put some bound on the number of simplices involved.

Lemma 3.8. *If the strong combinatorial thickness of I is $< \epsilon$, then we can find some $J \leq k + 2$ and simplices $\Delta_1, \dots, \Delta_J \subset X'$ with no common vertex, so that the map I lies in $\text{Bad}_\epsilon(\Delta_1, \dots, \Delta_J)$.*

Proof. Since I has combinatorial thickness $< \epsilon$ it lies in some set $\text{Bad}_\epsilon(\Delta_1, \dots, \Delta_J)$, where a priori J may be too large. We have to find a subset of $(k+2)$ of the simplices $\Delta_1, \dots, \Delta_J$ with no common vertex. We include Δ_1 in the subset. We let v_1, \dots, v_{k+1} be the vertices of Δ_1 . For each vertex v_i , we can find a simplex that does not contain v_i , because no vertex lies in all of the simplices. In this way, we choose $\leq k + 1$ more simplices, and no vertex lies in all of them. \square

From now on, we only consider bad sets with at most $k + 2$ simplices.

As in the proof of Theorem 2.1, most of the sets $\text{Bad}_\epsilon(\Delta_1, \dots, \Delta_J)$ are empty. They are non-empty only if all of the sets $I_0(\Delta_i)$ intersect a single ball of radius $(1 + \epsilon) < 2$. From now on, we consider only the non-empty sets. We say that a vertex $v \in X'$ is involved in a bad set $\text{Bad}_\epsilon(\Delta_1, \dots, \Delta_J)$ if v is a vertex of one of the simplices $\Delta_1, \dots, \Delta_J$. A ball of radius 2 intersects $\lesssim \log N$ simplices of X' . Therefore, each vertex v_i is involved in $\lesssim (\log N)^{k+1}$ bad sets $\text{Bad}_\epsilon(\Delta_1, \dots, \Delta_J)$. On the other hand, the number of vertices involved in a single bad set $\text{Bad}_\epsilon(\Delta_1, \dots, \Delta_J)$ is $\leq (k + 1)J \leq (k + 1)(k + 2)$. The last main ingredient is a bound for the probability of a bad set: the probability of any set $\text{Bad}_\epsilon(\Delta_1, \dots, \Delta_J)$ is $\lesssim \epsilon^\alpha$ for some power $\alpha > 0$.

Lemma 3.9. *Let $J \leq k + 2$. Then the probability of any bad set $\text{Bad}_\epsilon(\Delta_1, \dots, \Delta_J)$ is $\lesssim \epsilon^{\frac{1}{k+1}}$.*

This inequality is probably not sharp. I believe that the probability of $\text{Bad}_\epsilon(\Delta_1, \dots, \Delta_J)$ is $\lesssim \epsilon$, but I don't know how to prove it. This lemma is good enough for our application.

The rest of the proof of Proposition 3.7 is the same as the proof of Theorem 2.1. We summarize it here. We choose v_1, v_2, \dots . As we make each choice, we keep track of the conditional probability of the sets $Bad_\epsilon(\Delta_1, \dots, \Delta_J)$. When we pick v_i , the conditional probability of $Bad_\epsilon(\Delta_1, \dots, \Delta_J)$ changes only if v_i is a vertex of Δ_1, \dots , or Δ_J . So the choice of v_i affects $\lesssim (\log N)^{k+1}$ conditional probabilities. Therefore, we can choose v_i so that the conditional probabilities of $Bad_\epsilon(\Delta_1, \dots, \Delta_J)$ increase by at most a factor $\lesssim (\log N)^{k+1}$. Each bad set $Bad_\epsilon(\Delta_1, \dots, \Delta_J)$ involves $\leq (k+1)J \leq k^2 + 3k$ vertices. Therefore, after we have chosen all v_i , the conditional probability of $Bad_\epsilon(\Delta_1, \dots, \Delta_J)$ has increased by a factor $\lesssim (\log N)^{(k+1)(k^2+3k)}$. Since the probability of $Bad_\epsilon(\Delta_1, \dots, \Delta_J)$ was $\lesssim \epsilon^{\frac{1}{k+1}}$ before making any choices, after all our choices, the conditional probability of $Bad_\epsilon(\Delta_1, \Delta_2)$ is $\lesssim \epsilon^{\frac{1}{k+1}} (\log N)^{Ck^3}$. Of course, once we have chosen all $I(v_i)$, the conditional probability of $Bad_\epsilon(\Delta_1, \dots, \Delta_J)$ is either 1 or 0, depending on whether our choice lies in $Bad_\epsilon(\Delta_1, \dots, \Delta_J)$ or not. We pick ϵ sufficiently small so that all conditional probabilities of bad sets are strictly less than 1. This ϵ is $\sim (\log N)^{-Ck^4}$. Now our choice of the map I does not lie in any of the sets $Bad_\epsilon(\Delta_1, \dots, \Delta_J)$, and I has strong combinatorial thickness $\geq \epsilon \gtrsim (\log N)^{-Ck^4}$.

It remains only to prove Lemma 3.9. This proof consists of a quantitative analysis of the standard general position argument for linear maps. Quantitative analysis of general position arguments for random linear maps is an important, well-studied area in numerical analysis, see [De] and [BCL]. We use here a fundamental result from this area, which estimates the probability that the determinant of a random matrix is small.

Proposition 3.10. *Let M be a $d \times d$ matrix. Consider M as a point in \mathbb{R}^{d^2} . Suppose that M is chosen uniformly at random from the unit ball in \mathbb{R}^{d^2} . Then for any $\delta > 0$, with probability $(1 - \delta)$, $|Det(M)| \geq c(d)\delta$. Hence, with probability $(1 - \delta)$, the norm of M^{-1} is $\leq c'(d)\delta^{-1}$.*

I don't know who first proved this estimate. It appears in [De]. There is a thorough proof in [BCL]. In these references, they give very precise information about the asymptotics of $c(d)$ and $c'(d)$, which is important for numerical linear algebra and other applications. The following generalization of this estimate is an immediate corollary.

Proposition 3.11. *Let μ be a probability measure on the space of $d \times d$ matrices \mathbb{R}^{d^2} . Suppose that μ is supported on a ball of radius $\lesssim 1$ and that the density function of μ is pointwise $\lesssim 1$. Then for any $\delta > 0$, with probability $(1 - \delta)$, $|Det(M)| \geq c(d)\delta$. Hence, with probability $(1 - \delta)$, the norm of M^{-1} is $\leq c'(d)\delta^{-1}$.*

Using Proposition 3.11, we can bound the chance that two faces of $I(X')$ are too close together. (Recall that I is a random perturbation of size 1 from the initial embedding I_0 , and we want to measure the probability that two faces are very close together after the random perturbation.) In the following, we use Δ_i to refer to simplices of $I(X')$. We write P_i to refer to the plane spanned by Δ_i .

Proposition 3.12. *If Δ_1 and Δ_2 are simplices of $I(X')$ with no vertices in common, then $N_{\epsilon_1}(\Delta_1)$ and $N_{\epsilon_2}(\Delta_2)$ are disjoint with probability $1 - \delta$ for $\delta \lesssim (\epsilon_1 + \epsilon_2)$. Moreover, $N_{\epsilon_1}(P_1)$ and $N_{\epsilon_2}(P_2)$ are disjoint with probability $1 - \delta$ for $\delta \lesssim (\epsilon_1 + \epsilon_2)$.*

Proof. Let v_0, \dots, v_j be the vertices of Δ_1 and v_{j+1}, \dots, v_l be the vertices of Δ_2 . Since Δ_1 and Δ_2 have dimension $\leq k$, the number l is at most $2k+1 \leq n$. We translate our coordinates so that v_0 is at zero. If $N_{\epsilon_1}(P_1)$ and $N_{\epsilon_2}(P_2)$ intersect, then we can choose affine combinations $c_0 v_0 + \dots + c_j v_j$ and $c_{j+1} v_{j+1} + \dots + c_l v_l$ which lie within $\epsilon_1 + \epsilon_2$ of each other. In other words, $|c_0 \cdot 0 + c_1 v_1 + \dots + c_j v_j - c_{j+1} v_{j+1} - \dots - c_l v_l| \leq \epsilon_1 + \epsilon_2$. We let \vec{c} denote the l -dimensional column vector $(c_1, \dots, c_j, -c_{j+1}, \dots, -c_l)$. We let M denote the $l \times l$ matrix whose i^{th} column is given by the first l components of v_i . Then $|M\vec{c}| \leq \epsilon_1 + \epsilon_2$. Because $\sum_{j+1}^l c_i = 1$, $|\vec{c}| \sim 1$. Hence we get $|M^{-1}| \gtrsim (\epsilon_1 + \epsilon_2)^{-1}$.

The matrix M depends on the coordinates of the vertices v_i of Δ_1 and Δ_2 . The vertices are chosen uniformly at random in unit balls. Therefore, M is chosen by a probability distribution which obeys the hypotheses of Proposition 3.11. Hence the probability that $|M^{-1}| \gtrsim (\epsilon_1 + \epsilon_2)^{-1}$ is $\lesssim (\epsilon_1 + \epsilon_2)$. \square

Similarly, if Δ_1 and Δ_2 have vertices in common, then with high probability, $N_{\epsilon_1}(P_1) \cap N_{\epsilon_2}(P_2)$ lies near to $P_1 \cap P_2$.

Proposition 3.13. *For any $\delta > 0$, with probability $(1 - \delta)$, $N_{\epsilon_1}(P_1) \cap N_{\epsilon_2}(P_2)$ lies in $N_\epsilon(P_1 \cap P_2)$ for $\epsilon \sim \delta^{-1}(\epsilon_1 + \epsilon_2)$.*

Proof. Suppose that there is a point x in $N_{\epsilon_1}(P_1) \cap N_{\epsilon_2}(P_2)$ but not in the ϵ -neighborhood of $P_1 \cap P_2$.

Let w_0, \dots, w_j be the vertices of $\Delta_1 \cap \Delta_2$. The plane spanned by w_0, \dots, w_j is $P_1 \cap P_2$ (almost surely). Let v_1, \dots, v_l be the other vertices of Δ_1 . Let v_{l+1}, \dots, v_m be the other vertices of Δ_2 . We project to the orthogonal complement of $P_1 \cap P_2$. In this orthogonal complement, we make the image of $P_1 \cap P_2$ the origin. We denote the projection of v_i to the orthogonal complement by \bar{v}_i . The projection of Δ_1 is a simplex spanned by $0, \bar{v}_1, \dots, \bar{v}_l$. The projection of Δ_2 is a simplex spanned by $0, \bar{v}_{l+1}, \dots, \bar{v}_m$. The complement has dimension $n - j$, and because of the dimension assumptions on Δ_1, Δ_2 , we see that $m \leq n - j$.

We know that x lies in $N_{\epsilon_1}(P_1) \cap N_{\epsilon_2}(P_2)$. The projection of x lies within ϵ_1 of some vector in the projection of P_1 , which has the form of an affine combination $c_0 \cdot 0 + c_1 \bar{v}_1 + \dots + c_l \bar{v}_l$. Since x does not lie in $N_\epsilon(P_1 \cap P_2)$ the projection of x has norm $> \epsilon$. Therefore, $|\sum_{i=1}^l c_i| \gtrsim \epsilon$.

The projection of x also lies within ϵ_2 of some vector in the projection of P_2 , which has the form of an affine combination $d_0 \cdot 0 + d_1 \bar{v}_{l+1} + \dots + d_{m-l} \bar{v}_m$. Therefore, these two points are close to each other:

$$|c_1 \bar{v}_1 + \dots + c_l \bar{v}_l - d_1 \bar{v}_{l+1} - \dots - d_{m-l} \bar{v}_m| \leq \epsilon_1 + \epsilon_2. \quad (*)$$

We let \vec{c} be the vector $(c_1, \dots, c_l, -d_1, \dots, -d_{m-l})$. It has m entries. We let M be the $m \times m$ matrix with columns given by the first m entries of \bar{v}_i . Inequality $(*)$ implies that $|M\vec{c}| \leq \epsilon_1 + \epsilon_2$. Since $|\sum_{i=1}^l c_i| > \epsilon$, we see that $|\vec{c}| \gtrsim \epsilon$ and so $|M^{-1}| \gtrsim \epsilon(\epsilon_1 + \epsilon_2)^{-1}$.

Now the entries of M depends on the randomly chosen positions of the vertices of Δ_1 and Δ_2 , and it's not hard to check that M is a random matrix obeying the conditions of Proposition 3.11. Therefore, the probability that $|M^{-1}| \gtrsim \epsilon(\epsilon_1 + \epsilon_2)^{-1}$ holds is $\lesssim \epsilon^{-1}(\epsilon_1 + \epsilon_2)$. \square

With these tools, we are ready for the proof of Lemma 3.9.

Proof of Lemma 3.9. We have a sequence of simplices of $I(X')$, $\Delta_1, \Delta_2, \dots, \Delta_J$, with $J \leq k + 2$. We know that $\cap_{j=1}^J \Delta_j$ is empty, and we can assume that $\cap_{i=1}^{J-1} \Delta_i$ is not empty. We inductively analyze the intersection $\cap_{i=1}^j N_\epsilon(P_i)$.

Inductive claim. For any $\delta > 0$, for each $1 \leq j \leq J - 1$, the following estimate holds with probability $(1 - j\delta)$:

$$\cap_{i=1}^j N_\epsilon(P_i) \subset N_{C\delta^{1-j}\epsilon}(\cap_{i=1}^j P_i).$$

Proof of claim. The case $j = 1$ is trivial. The step from $j - 1$ to j follows from Proposition 3.13. Note that $\cap_{i=1}^j P_i$ is the plane spanned by $\cap_{i=1}^j \Delta_i$.

Now $\cap_{j=1}^{J-1} \Delta_i$ and Δ_J are disjoint. So Proposition 3.12 tells us that $N_{C\delta^{2-J}\epsilon}((\cap_{i=1}^{J-1} P_i)$ and $N_\epsilon(P_J)$ intersect with probability $\lesssim \delta^{2-J}\epsilon$.

Hence $\cap_{j=1}^J N_\epsilon(\Delta_j)$ is non-empty with probability $\lesssim \delta + \delta^{2-J}\epsilon \leq \delta + \delta^{-k}\epsilon$. At this point we choose δ to optimize our bound: $\delta = \epsilon^{\frac{1}{k+1}}$. □

3.5. Open questions. Let us say that the retraction-thick embedding radius of X^k into \mathbb{R}^n is the smallest R so that X^k embeds with retraction thickness 1 into $B^n(R)$.

Suppose that X^k is a simplicial complex with N simplices and with each vertex lying in $\lesssim 1$ simplices. How big can the retraction-thick embedding radius of X be?

For $k = 1$, the retraction thick embedding radius of X must be $\lesssim N^{1/n}$, and this is sharp. For $k \geq 2$, we don't know what happens.

By Theorem 3.1, the retraction-thick embedding radius of X^k into \mathbb{R}^n is $\lesssim N^{\frac{1}{n-k}+\epsilon}$.

For example, the retraction-thick embedding radius of X^2 into \mathbb{R}^n is $\lesssim N^{\frac{1}{n-2}+\epsilon}$. But in the examples that we could work out, the retraction thick embedding radius was at most $N^{\frac{1}{n}}$. Which 2-complexes are hardest to embed in Euclidean space?

The most complicated complexes that we considered were the arithmetic hyperbolic manifolds of dimension $k \geq 3$. The retraction-thick embedding radius of such X into \mathbb{R}^n is $\gtrsim N^{\frac{1}{n-1}}$. The most difficult complexes are probably not manifolds. What are they, and how can we exploit them? For example, one may want to consider k -skeleta of higher-dimensional arithmetic manifolds or Garland buildings as in [Gr2].

On the other hand, one may ask how big the retraction-thick embedding radius can be for a manifold X^k embedded in \mathbb{R}^n , if X can be triangulated with N simplices. For $k = 1, 2$, the retraction-thick embedding radius is $\lesssim N^{1/n}$, and this is sharp. For $k = 3$, the situation is unclear. The retraction-thick embedding radius is $\lesssim N^{\frac{1}{n-3}}$. For arithmetic hyperbolic 3-manifolds, it is $\gtrsim N^{\frac{1}{n-1}}$. Are arithmetic hyperbolic 3-manifolds the hardest 3-manifolds to embed in Euclidean space? What is their actual retraction-thick embedding radius?

4. DISTORTION OF KNOTS

Given a set $K \subset \mathbb{R}^n$, we write $dist_K$ to denote the intrinsic distance in K : $dist_K(y, z)$ denotes the infimal length of a path in K from y to z . The distortion of K measures the ratio between the intrinsic distance and the extrinsic distance:

$$distor(K) := \sup_{x, y \in K} \frac{dist_K(x, y)}{dist_{\mathbb{R}^3}(x, y)}.$$

In this section, we discuss the distortion of knots $K \subset \mathbb{R}^3$. The distortion is a scale-invariant measure of the geometric complexity of a knot K . We want to understand how the distortion of a knot is related to the topology of the knot. One fundamental question is whether there are isotopy classes of knots that require arbitrarily large distortion. This question was raised in the early 1980's ([Gr3]), and it was open for many years. Recently the question was resolved by Pardon.

Theorem 4.1. (*Pardon, [P]*) *There are isotopy classes of knots in \mathbb{R}^3 requiring arbitrarily large distortions.*

In this section we give an alternate proof of Theorem 4.1.

Let's say a little about why the problem is difficult. First of all, there are infinitely many isotopy classes of knots with distortion < 100 . For example, one may consider a long chain of simple knots. Such a long chain is reducible, but there are also infinitely many irreducible isotopy classes. For example, take a long chain of simple knots, and then loop each knot in the chain through the adjacent knots. See [0] for details. A knot of distortion < 100 may also be knotted at arbitrarily many different scales: take a trefoil knot, and then zoom in on a small nearly straight curve and replace it by a small trefoil knot, and then zoom in on it, etc. No matter how many times we repeat such an operation, the distortion will be < 100 . Also, one may replace trefoils by other simple knots: figure eight knots, etc. Let $K(D)$ denote the set of isotopy classes of knots with distortion $< D$. One might like to find a knot invariant which is uniformly bounded on $K(100)$, and then to find another knot K' where the invariant is outside these bounds. Then we could conclude that K' cannot be isotoped to have distortion < 100 . But $K(100)$ contains infinitely many knots, and it appears that all standard invariants are unbounded on $K(100)$. (For example, one may consider the genus of the knot, the unknotting number, the degree of the Alexander polynomial, the size of the coefficients of the Alexander polynomial, the degree or size of other knot polynomials, the size of some Vassiliev invariant, etc. I suspect that these are all unbounded on $K(100)$.)

On the other hand, there are many isotopy classes of knots that appear to have large distortions. For example, the torus knots $T_{p,q}$ appear to have large distortion if p or q is large. Pardon gave the following bound for distortion of torus knots.

Distortion of torus knots. ([P]) *If K is a (p, q) -torus knot with $2 \leq p < q$, then the distortion of K is $\gtrsim p$.*

This lower bound is sharp in some cases. For example, the distortion of $T_{p,p+1}$ is $\lesssim p$. But in other cases it looks far from sharp. For example, it appears that the distortion of $T_{2,q}$ is $\sim q$. (The results in [P] also apply to knots on higher-genus surfaces.)

Pardon's argument and our argument both involve another measure of the geometric complexity of a knot, called the conformal length. Define the conformal length of a knot $K \subset \mathbb{R}^3$ as

$$\sup_{x \in \mathbb{R}^3, r > 0} r^{-1} \text{length}[K \cap B(x, r)].$$

Similarly, we can define the conformal k -volume for any k -dimensional polyhedron in \mathbb{R}^n . We denote conformal k -volume by convol_k and in particular conformal length by convol_1 . The conformal volume is a small variation of a conformal invariant defined by Li and Yau in [LY].

The conformal length is another scale-invariant measure of the geometric complexity of a knot K . It is related to the distortion by the following lemma, which essentially appears in [P].

Lemma 4.1. *If $K \subset \mathbb{R}^3$ is a knot, then*

$$\text{convol}_1(K) \leq 4 \text{distor}(K).$$

Proof. Pick any $x \in \mathbb{R}^3$ and $r > 0$. Let L denote the length of $K \cap B(x, r)$. We have to prove that $L/r \leq 4 \text{distor}(K)$.

Pick two points y, z in $K \cap B(x, r)$ so that $\text{dist}_K(y, z)$ is at least $L/2$. On the other hand, $\text{dist}_{\mathbb{R}^3}(y, z) \leq 2r$.

$$\frac{L}{4r} \leq \frac{\text{dist}_K(y, z)}{\text{dist}_{\mathbb{R}^3}(y, z)} \leq \text{distor}(K).$$

□

Therefore, proving that a knot has large conformal length is even stronger than proving that it has large distortion. In [P], Pardon estimated the conformal length of torus knots.

Conformal lengths of torus knots. ([P]) *If K is a (p, q) -torus knot with $2 \leq p < q$, then the conformal length of K is $\gtrsim p$.*

This estimate is sharp up to constant factors for every torus knot: the knot $T_{p,q}$ can be realized with conformal length $\lesssim p$. The knot $T_{p,q}$ can be thought of as a braid with p strands, where the two ends of the braid are connected up in a simple way. Any p -strand knot can be arranged to have conformal length $\lesssim p$ by making the strands very long and having them move around each other slowly.

We will prove lower bounds for conformal lengths of knots associated to arithmetic hyperbolic 3-manifolds. To define these knots, we recall a theorem of Montesinos and Hilden.

Ramified cover theorem. ([H], [M]) *Any closed oriented 3-manifold M admits a degree 3 map $M \rightarrow S^3$ which is a ramified cover ramified over a knot.*

When M is a complicated hyperbolic manifold, and M has a degree 3 map to S^3 ramified over a knot K , then we prove that K has a large conformal length.

Theorem 4.2. *If M is a closed oriented hyperbolic 3-manifold with volume V and Cheeger constant h , and if $F : M \rightarrow S^3$ is a 3-fold cover ramified over a knot K , then the conformal length of K is $\gtrsim hV$.*

We will measure the conformal length of K in \mathbb{R}^3 . We pick any point $q \in S^3 \setminus K$, and we identify $S^3 \setminus q$ with \mathbb{R}^3 . The resulting knot K in \mathbb{R}^3 always has conformal length $\gtrsim hV$. (With a similar argument, one can also bound the conformal length of K in S^3 with the round metric.)

The conclusion also applies to any knot K' isotopic to K . Suppose that $\Psi : S^3 \rightarrow S^3$ is a diffeomorphism taking K to K' . Then $\Psi \circ F : M \rightarrow S^3$ is a degree 3 cover ramified over K' - and so the conformal length of K' is also $\gtrsim hV$.

The most interesting examples occur when M is an arithmetic hyperbolic 3-manifold. See the appendix for more background on arithmetic hyperbolic 3-manifolds. Suppose that we take a fixed closed arithmetic hyperbolic 3-manifold M_0 and then look at a sequence of arithmetic covers M_i with volume $V_i \rightarrow \infty$. Remarkably, the Cheeger constants of these M_i are bounded below uniformly: $h_i \geq c > 0$. Applying the Hilden-Montesinos theorem, we can map $M_i \rightarrow S^3$ degree 3 ramified over a knot K_i . By Theorem 4.2, the conformal length of K_i is $\gtrsim V_i \rightarrow +\infty$. In particular, the distortion of K_i is $\gtrsim V_i \rightarrow +\infty$. So Theorem 4.2 implies Theorem 4.1.

Our lower bound for the conformal length is essentially sharp in this example. If M_i is a degree D_i cover of M_0 , then $D_i \sim V_i$. If G_0 denotes the Heegaard genus of M_0 , then the Heegaard genus of M_i is $G_i \leq D_i G_0 \lesssim V_i$. Hilden's construction of the degree 3 cover $M_i \rightarrow S^3$ ramified over K_i is based on a Heegaard decomposition of M_i . The construction of K_i gives a braid with $\lesssim G_i$ strands, capped at each end in a simple way. Now we can isotope K_i so that the braid is very long and the strands move around each other very slowly. For such a knot K_i , the conformal length is $\lesssim G_i \lesssim V_i$. On the other hand, it's not clear how sharp our lower bound for the distortion of K_i is.

Here is an outline of our proof. One way to understand the complexity of a knot K is to build a triangulation of S^3 so that the knot is an embedded curve in the 1-skeleton. If the triangulation is not too complicated, then the knot cannot be too complicated either. We use our information about the conformal length of K to build such a triangulation which is "not too big". Now, the simplest way to measure the size of a triangulation is the number of simplices. But we cannot bound the number of simplices in the triangulation in terms of the conformal length of K , or even in terms of the distortion of K . This is just because there are infinitely many different knots with distortion < 100 . Instead, we bound a kind of "width" of the triangulation.

More precisely, we build a simplicial map G from our triangulated 3-sphere (S^3, Tri_0) to a tree T so that every fiber of the map is small. The fiber over a vertex of T is a

2-dimensional subcomplex of (S^3, Tri_0) containing $\lesssim \text{convol}_1(K)$ simplices, and the fiber over an edge of T also contains $\lesssim \text{convol}_1(K)$ simplices.

The main difficulty in building this triangulation is just to find a map from S^3 to a tree T whose fibers have controlled topology and don't intersect K too many times. In particular, we find a map $S^3 \rightarrow T$ where every fiber intersects K in $\lesssim \text{convol}_1(K)$ points and where each fiber is homotopic to a 2-sphere or to a bouquet of 2-spheres with $\lesssim 1$ spheres.

To get an idea how the conformal length may be used to construct such a map, consider a cube $Q \subset \mathbb{R}^3$ with side-length s . We know that the length of $K \cap 2Q$ is $\lesssim \text{convol}_1(K)s$. Now if we translate Q by a random vector of length $\leq s$, the average number of intersections between K and ∂Q is $\lesssim \text{convol}_1(K)$. The fibers of the map F will be the boundaries of this kind of cube (or the union of a few such boundaries).

In the second half of the proof, we connect this nice triangulation with the hyperbolic geometry of M . Since $F : M \rightarrow S^3$ is a degree 3 cover ramified over K , and since K is embedded in the 1-skeleton of our triangulation Tri_0 , we can lift Tri_0 to a triangulation Tri of M . Composing F and G , we get a simplicial map from (M, Tri) to the tree T with small fibers. We can exploit the hyperbolic geometry of M by straightening the simplices of Tri . The simplex straightening gives a map $S : (M, Tri) \rightarrow (M, hyp)$, homotopic to the identity, mapping each 2-simplex of Tri to a geodesic 2-simplex of (M, hyp) with area $\lesssim 1$ and each 3-simplex of Tri to a geodesic 3-simplex of (M^3, hyp) with volume $\lesssim 1$.

Now in rough terms, the straightened version of (M, Tri) is “thin” - it has “width” $\lesssim \text{convol}_1(K)$. On the other hand, the hyperbolic manifold (M, hyp) is “wide” - it has width $\gtrsim hV$. Since the straightening map S has degree 1, (M, Tri) must be wide enough to fit around (M, hyp) and so $\text{convol}_1(K) \gtrsim hV$.

The last step of this argument is similar to an estimate from [Gr1], which says that a sufficiently generic map from M^3 to a tree T has a fiber with genus $\gtrsim hV$. We include a self-contained proof which is adapted to our situation, but the main idea comes from [Gr1].

We remark that our lower bound for the distortion of the knot K is ultimately powered by the expander properties of arithmetic hyperbolic 3-manifolds. So to some extent, this theorem may be considered a generalization of the Kolmogorov-Barzdim estimate on the difficulty of embedding an expander into \mathbb{R}^3 .

Now we turn to the detailed proof of the theorem.

Proof of Theorem 4.2. It is convenient to assume that the knot K is piecewise linear. If the knot is originally smooth or piecewise smooth, we can approximate it by a PL knot with a negligible effect on the conformal length. By making a small generic rotation, we can also assume that the edges of K are transverse to the coordinate planes.

Step 1. Cutting blocks into pieces

A key step in the proof is a lemma allowing us to cut a rectangular block into pieces that intersect K nicely.

If a rectangular block has dimensions $L_1 \times L_2 \times L_3$ with $L_1 \leq L_2 \leq L_3$, then we call the ratio L_3/L_1 the eccentricity of the block.

Block decomposition lemma. *Let $Q \subset \mathbb{R}^3$ be a rectangular block of eccentricity < 10 , and suppose that each face of Q intersects K at most $1000\text{convol}_1(K)$ times. Then we can decompose Q into smaller blocks with eccentricity < 10 so that each face of each smaller block intersects K at most $1000\text{convol}_1(K)$ times.*

The number of smaller blocks will be at least 8 and at most 2000. Each smaller block has maximal side length at most $L_1(Q)/2$, where $L_1(Q)$ denotes the smallest side length of Q .

Proof. Let X denote the 2-skeleton of a cubical lattice with side length $L_1(Q)/2$. (We assume that the axes of X are parallel to the axes of Q .) We will make a random translation of X . The translated X decomposes Q into rectangular blocks. We will prove by a probabilistic argument that some translations of X decompose Q into pieces that satisfy our conclusions.

We begin with the easy conclusions. Because X is a lattice with spacing $L_1(Q)/2$, all of the blocks in the decomposition have all side lengths $\leq L_1(Q)/2$. By the bound on the eccentricity of Q , the lengths $L_2(Q), L_3(Q)$ lie in the range $L_1(Q) \leq L_2(Q), L_3(Q) \leq 10L_1(Q)$. So the number of blocks in the decomposition is at least 8 and at most $(3)(21)(21) \leq 2000$.

Next we consider the probability that all the blocks in the decomposition have eccentricity < 10 . Since all blocks have maximal side length $\leq L_1(Q)/2$, it suffices to check that they have minimal side length $> L_1(Q)/20$. The only thing that may go wrong is that one of the planes of X may lie within $L_1(Q)/20$ of a parallel face of Q . For each face, the probability of this happening is $1/10$. Therefore, with probability at least $(4/10)$, all of the cubes in the decomposition have eccentricity < 10 .

Next we consider the intersection $X \cap Q \cap K$. We take the average over all translations of X . Integral geometry will allow us to bound this average in terms of $\text{length}(K \cap Q)$. Our X is a union of planes in different directions. We write $X_{12} \subset X$ to denote the union of the planes in the $x_1 - x_2$ direction, and so on. Hence $X = X_{12} \cup X_{13} \cup X_{23}$.

Integral geometry tells us that the average number of intersections between X_{12} and $K \cap Q$ is

$$\leq \frac{\text{length}(K \cap Q)}{L_1(Q)/2}.$$

Therefore, the average number of intersections between X and $K \cap Q$ is

$$\leq \frac{3\text{length}(K \cap Q)}{L_1(Q)/2}.$$

Now Q is contained in a ball of radius at most $10L_1(Q)$. Therefore, the length of $K \cap Q$ is $\leq 10L_1(Q)\text{convol}_1(K)$. So the average number of intersections between X and $K \cap Q$ is $\leq 60\text{convol}_1(K)$.

Therefore, we can find a translate of X so that all the blocks in the decomposition have eccentricity < 10 and also X intersects $K \cap Q$ in $\leq 150\text{convol}_1(K)$ points.

Finally, we let Q_i be any rectangular block in the decomposition. Any face of Q_i is either part of X or part of a face of Q . Hence the number of times that K intersects this face is $\leq 1000 \text{convol}_1(K)$. \square

Step 2. A tree of nested rectangles

Using the block decomposition lemma repeatedly, we will cut space into a tree of nested rectangular blocks so that each face of each block intersects K in $\lesssim \text{convol}_1(K)$ points. The largest rectangle will contain K , the smallest rectangle will intersect K in simple segments, and the regions between consecutive rectangles will intersect K in a controlled way.

We now give a more detailed description of the objects we will construct. (We will construct them below, by using the block decomposition lemma repeatedly.)

We let Q_0 be a large cube containing K . The cube Q_0 is sub-divided into rectangular blocks B_i . Inside of each block B_i , we choose a slightly smaller nested rectangle Q_i . We will construct a mapping from Q_0 to a tree T . The boundary of Q_0 and the boundaries of the B_i are mapped to the root vertex v_0 . The boundaries of the Q_i are mapped to vertices v_i adjacent to v_0 . The region $B_i \setminus Q_i$ is mapped to the edge between v_0 and v_i .

Now we repeat the above construction inside each rectangle Q_i . Each rectangle Q_i is divided into rectangular blocks B_{ij} . Inside each B_{ij} , we choose a slightly smaller nested rectangle Q_{ij} . The boundaries of all the blocks B_{ij} are mapped to v_i . The boundary of Q_{ij} is mapped to v_{ij} , a vertex adjacent to v_i . The region $B_{ij} \setminus Q_{ij}$ is mapped to the edge from v_i to v_{ij} .

This process repeats a large finite number of times. At the end, we are left with a certain number of terminal rectangles Q_α , where α is a multi-index. The boundary of Q_α is mapped to v_α . We let x_α denote a point in the interior of Q_α (we will choose x_α later). We map x_α to a vertex $v_{\alpha,+}$, and we map the interior of Q_α to the edge from v_α to $v_{\alpha,+}$.

These objects obey the following estimates.

Property 1. Each face of any Q_α or B_α intersects $K \leq 1000 \text{convol}_1(K)$ times.

Property 2. Each region $B_\alpha \setminus Q_\alpha$ does not contain any of the vertices of K . (Recall that K is a PL curve consisting of finitely many straight edges connected at vertices.) Moreover, each region $B_\alpha \setminus Q_\alpha$ meets K in $\leq 1000 \text{convol}_1(K)$ straight segments with length very small compared to the distance between the segments - and each segment enters through an open face of B_α and exits through the corresponding face of Q_α .

Property 3. Each terminal Q_α intersects K in either part of a single edge, or one vertex and part of two adjacent edges, or not at all.

Property 4. Each Q_α is subdivided into at most 2000 blocks $B_{\alpha,j}$.

We now construct the Q 's and the B 's, and prove that they have Properties 1-4.

We let Q_0 be a large cube containing K in its interior. The boundary of Q_0 does not intersect K , so Q_0 obeys all desired estimates.

We use the block decomposition lemma to divide Q_0 into rectangular blocks B_i . The lemma tells us that B_i obeys Property 1, and that the number of blocks B_i is at most 2000, confirming Property 4. By choosing the blocks B_i in general position, we can assume that the faces of B_i never contain vertices of K and that the 1-dimensional edges of ∂B_i never

intersect K . So the blocks B_i obey all the desired Properties. Moreover, we know that each block B_i has eccentricity < 10 , and we know that the diameter of B_i is $\leq (1/2)\text{diam}(Q_0)$.

Next we choose *slightly* smaller nested blocks Q_i in each B_i . By choosing Q_i very close to B_i , we can arrange that $B_i \setminus Q_i$ does not contain any vertices of K . Then by choosing Q_i even closer to B_i we can arrange all of Property 2. (At this step, we use that the edges of K are transverse to the coordinate planes and hence to the faces of B_i .) Since each edge of K passing through a face of Q_i passes through the corresponding face of B_i , we see that Q_i obeys Property 1 also. Therefore, the cubes Q_i obey all the desired properties. Moreover, since Q_i is very close to B_i we can arrange that the eccentricity of Q_i is < 10 , and we know that $\text{diam}(Q_i) < (1/2)\text{diam}(Q_0)$.

Now we proceed inductively. Since Q_i has eccentricity < 10 and each face of Q_i meets K in $< 1000\text{convol}_1(K)$ edges, we can apply the block decomposition lemma to divide Q_i into blocks B_{ij} . Just as above, we check that the B_{ij} obey the Properties. Then we choose a nested rectangular block $Q_{ij} \subset B_{ij}$ just slightly smaller than B_{ij} , and we check as above that Q_{ij} obeys all the desired properties. Moreover, the Q_{ij} still have eccentricity < 10 and diameter $< (1/2)^2\text{diam}(Q_0)$. We can then repeat this procedure as many steps as we want, and the diameters of the cubes decrease exponentially as we go.

To decide when to stop, we let ϵ denote the minimum of the shortest length of an edge of K and the smallest distance between two non-adjacent edges of K . We repeat the above subdivision process D times, where we choose D so that $2^{-D}\text{diam}(Q_0) < \epsilon$. Every terminal cube Q_α has diameter $< \epsilon$, and so it obeys Property 3.

Step 3. A thin triangulation of S^3

In Step 2, we cut Q_0 into pieces (nested rectangles) that intersect K in a simple way. Now we triangulate Q_0 by cutting each piece into simplices. We do this so that the knot K ends up in the 1-skeleton of the triangulation, and at the same time, each of the pieces is not too complicated.

We express our control of the triangulation in terms of a simplicial map from the triangulated sphere to a tree T . We say that a simplicial map from a triangulated 3-manifold to a graph is non-degenerate if the image of each 3-simplex is an edge of the graph. In other words, a non-degenerate map does not collapse a 3-dimensional simplex to a vertex.

Lemma 4.2. *If $K \subset S^3$ is a knot, then we can triangulate S^3 by a triangulation Tri_0 containing K in its 1-skeleton with the following property. There is a non-degenerate simplicial map π_0 from (S^3, Tri_0) to a tree T obeying the following estimates.*

1. *For each edge e of T , the inverse image $\pi_0^{-1}(e)$ contains $\lesssim \text{convol}_1(K)$ simplices.*
2. *Each vertex of T lies in $\lesssim 1$ edges of T .*

Proof. Our triangulation is going to be built around the nested blocks from Step 2. In particular, the boundary of each B_α will be contained in the 2-skeleton of the triangulation. First we triangulate the faces of each ∂B_α . Second we triangulate the regions $B_\alpha \setminus Q_\alpha$. Finally, we triangulate the terminal cubes Q_α and the exterior of Q_0 .

First we triangulate the faces of B_i - the blocks at the first step. Each face meets K in $\leq 1000 \text{convol}_1(K)$ points. We use the Delaunay triangulation of each face using these points. So each face has $\leq 10^4 \text{convol}_1(K)$ simplices.

Next we triangulate the faces of Q_i . Because of Property 2 in Step 2, we can move the triangulation of each face of B_i to an equivalent triangulation of each face of Q_i . In fact, we can lift the triangulation of ∂B_i to a polyhedral structure on $B_i \setminus Q_i$ where the 3-dimensional faces are convex polyhedra combinatorially equivalent to $\Delta^2 \times [0, 1]$. Each segment of $K \cap (B_i \setminus Q_i)$ is contained in the 1-skeleton of this polyhedral structure.

Next we triangulate the faces of B_{ij} . Some faces of B_{ij} lie in ∂Q_i . We call these boundary faces. Other faces of B_{ij} lie in the interior of Q_i , and we call them interior faces. Each face of Q_i is subdivided into four boundary faces of four different blocks B_{ij} . We have already triangulated each face of Q_i , but we need to refine the triangulations to include the edges separating the four boundary faces. After we add these edges, each face of B_{ij} is divided into polygons. Each polygon is part of one of the simplices in the face of Q_i , and so the number of polygons is $\leq 10^4 \text{convol}_1(K)$. Also, each polygon is the intersection of a simplex with a rectangle, and so it has ≤ 7 sides.

Each interior face of B_{ij} we triangulate so that the intersections with K are vertices. We again use the Delaunay triangulation, and so we get a triangulation with $\leq 10^4 \text{convol}_1(K)$ simplices.

Now we continue inductively to finer and finer scales. At each scale, we get a polyhedral structure on each face of B_α with $\leq 10^4 \text{convol}_1(K)$ polygons which are each the intersection of a simplex with a rectangle. Hence they each have ≤ 7 sides. We also get a polyhedral structure on each region $B_\alpha \setminus Q_\alpha$ with $\leq 10^5 \text{convol}_1(K)$ polyhedra, where each 3-face has $\lesssim 1$ 2-faces in its boundary. We subdivide these polyhedra without adding vertices to get a triangulation. In each region $B_\alpha \setminus Q_\alpha$, this triangulation has $\lesssim \text{convol}_1(K)$ faces.

Finally, we do the terminal cubes Q_α . We have already triangulated the boundary of Q_α . If $K \cap Q_\alpha$ is a segment, then we let x_α be a point on the segment in the interior of Q_α . If $K \cap Q_\alpha$ is a vertex with two segments adjacent to it, we let x_α be the vertex, which lies in the interior of Q_α . If $K \cap Q_\alpha$ is empty, then we just let x_α be any point in the interior of Q_α . To triangulate the interior of Q_α , we take the cone of the triangulation of ∂Q_α with vertex $x_\alpha \in Q_\alpha$. Because of our choice of x_α , the intersection $K \cap Q_\alpha$ lies in the 1-skeleton of the triangulation. It has $\lesssim 1$ simplices.

Since ∂Q_0 did not intersect K , we triangulate it with $\lesssim 1$ faces, and then we can triangulate $S^3 \setminus Q_0$ by taking a cone from the triangulation of ∂Q_0 to the point at infinity. This completes our triangulation of S^3 .

The tree T is basically the same as in Step 2, but to deal with $S^3 \setminus Q_0$ we add one more vertex v_∞ and one more edge from v_∞ to v_0 . We map the point at ∞ to v_∞ . We map all the vertices in the boundary of B_i to v_0 . We map all the vertices in the boundary of B_{ij} to v_i , and so on. For a terminal cube Q_α , we map all the vertices in ∂Q_α to v_α . We map the vertex x_α in the center of a terminal cube Q_α to $v_{\alpha,+}$. Then we extend simplicially. The inverse image of an edge from v_α to $v_{\alpha,j}$ is the region $B_{\alpha,j} \setminus Q_{\alpha,j}$, which has $\lesssim \text{convol}_1(K)$ simplices. The inverse image of a terminal edge from v_α to $v_{\alpha,+}$ is the terminal cube Q_α ,

which has $\lesssim 1$ simplices. Similarly, the inverse image of the edge from v_0 to v_∞ is $S^3 \setminus Q_0$, which has $\lesssim 1$ simplices.

As in Step 2, the tree T has degree $\leq 2001 \lesssim 1$.

□

Step 4. A thin triangulation of M^3

Using our cover $F : M^3 \rightarrow S^3$ which is ramified over the knot K , we can pull the triangulation from Step 3 up to M . The resulting triangulation of M retains all the good characteristics of the triangulation of S^3 .

Lemma 4.3. *Suppose that M^3 is a closed oriented 3-manifold. Suppose that $F : M^3 \rightarrow S^3$ is a degree 3 cover ramified over a knot $K \subset S^3$. Then, there is a triangulation Tri of M^3 and a non-degenerate simplicial map π from (M^3, Tri) to a tree T obeying the following estimates.*

1. *For each edge e of T , the inverse image $\pi^{-1}(e)$ contains $\lesssim \text{convol}_1(K)$ simplices.*
2. *Each vertex of T lies in $\lesssim 1$ edges of T .*

Proof. Let Tri_0 be the triangulation of S^3 constructed in Step 3. Since K is contained in the 1-skeleton of Tri_0 , we can lift Tri_0 to a triangulation Tri of M^3 . The map $F : (M^3, Tri) \rightarrow (S^3, Tri_0)$ is a simplicial map. If Δ denotes a simplex of Tri_0 which is not contained in the knot K , then Δ lifts to three simplices in Tri . If Δ is an edge or vertex of Tri_0 which is contained in K , then Δ lifts to a single edge or vertex of Tri .

Let $\pi_0 : (S^3, Tri_0) \rightarrow T$ be the simplicial map to a tree constructed in Step 3. We define $\pi : (M^3, Tri) \rightarrow T$ to be the composition $\pi_0 \circ F$. This is also a simplicial map. The map F is non-degenerate in the sense that each 3-simplex of M^3 is mapped to a whole 3-simplex of S^3 . Therefore, π is non-degenerate as well. The number of simplices in $\pi^{-1}(e)$ is at most three times the number of simplices of Tri_0 in $\pi_0^{-1}(e)$, and so π obeys Property 1. The tree T is the same tree as in Step 3, and so it obeys Property 2. □

Step 5. Hyperbolic geometry

At this point, we connect the hyperbolic geometry of M with the combinatorial information about the triangulation (M, Tri) . In a bit more generality, we prove the following lemma.

Lemma 4.4. *Suppose that (M^3, Tri) is a triangulated manifold (or pseudomanifold), $\pi : (M^3, Tri) \rightarrow T$ is a non-degenerate simplicial map to a tree T of degree $\lesssim 1$, and that for each edge $e \subset T$, $\pi^{-1}(e)$ has $\leq A$ simplices. On the other hand, suppose that M^3 admits a map of non-zero degree modulo 2 to a closed hyperbolic manifold (N^3, hyp) with volume V and Cheeger constant h .*

Then $A \gtrsim hV$.

Given Lemma 4.3 and Lemma 4.4, we can quickly prove Theorem 4.2. We let Tri be the triangulation of M^3 from Lemma 4.3. Now (M^3, Tri) satisfies the first hypothesis of Lemma 4.4. $A \lesssim \text{convol}_1(K)$. Then we take (N^3, hyp) to be (M^3, hyp) . The identity map

from (M^3, Tri) to (M^3, hyp) has degree 1 modulo 2. All of the hypotheses of Lemma 4.4 are satisfied, and we conclude that $convol_1(K) \gtrsim hV$.

Now we turn to the proof of Lemma 4.4.

Proof of Lemma 4.4. We first apply simplex straightening to the map ϕ . After straightening, we may assume that $\phi(\Delta^2)$ has area $\lesssim 1$ for each 2-simplex Δ^2 in (M^3, Tri) and that $\phi(\Delta^3)$ has volume $\lesssim 1$ for each 3-simplex Δ^3 in (M^3, Tri) .

Now we can describe the intuition behind the lemma. The first hypothesis roughly means that the triangulated manifold M is “thin”. It looks morally like a thin neighborhood of a tree with thickness A . On the other hand, hV is the “thickness” of (N^3, hyp) . Since M fits around (N^3, hyp) , it forces M to be as thick as (N^3, hyp) and so $A \gtrsim hV$. The detailed proof follows.

The map $\pi : (M^3, Tri) \rightarrow T$ allows us to break (M^3, Tri) into smaller pieces. Namely, for each edge $e \subset T$, we define $Y(e) = \pi^{-1}(e)$. We view $Y(e)$ as a mod 2 3-chain. Because π maps every 3-simplex to exactly one edge of T , $\sum_{e \subset T} Y(e)$ is homologous to the fundamental class $[M]$.

Next the boundary of $Y(e)$ has a nice structure. Suppose that ∂e consists of the vertices v_1 and v_2 . Then $\partial Y(e)$ breaks into two parts, one over v_1 and one over v_2 . We write $\partial Y(e) = Z(e, v_1) + Z(e, v_2)$, where $Z(e, v) \subset \pi^{-1}(v)$. For any pair $v \in e$, where v is a vertex of T and e is an edge of T containing v , we have defined a 2-cycle $Z(e, v)$ in M^3 contained in $\pi^{-1}(v)$. Since $Z(e, v)$ is part of the boundary of $Y(e)$, each $Z(e, v)$ contains $\lesssim A$ simplices.

Because (M^3, Tri) is itself a 3-cycle, for each vertex v , $\sum_{e: v \in e} Z(e, v) = 0$. This holds because $\partial(\sum_{e \subset T} Y(e)) = 0$, and the part of this boundary in $\pi^{-1}(v)$ is exactly $\sum_{e: v \in e} Z(e, v)$.

Also, because T is a tree, each $Z(e, v)$ is null-homologous in M^3 . To see this, let T_0 be the component of $T \setminus v$ which contains e . Then $\pi^{-1}(T_0)$ defines a 3-chain with boundary $Z(e, v)$.

Next we consider mapping the Y 's and Z 's to (N^3, hyp) . We define $\bar{Y}(e)$ to be $\phi(Y(e))$ and $\bar{Z}(e, v)$ to be $\phi(Z(e, v))$. By the bound on the number of simplices of Y and Z and the straightness of ϕ , we can conclude that $\bar{Y}(e)$ has volume $\lesssim A$ and $\bar{Z}(e, v)$ has area $\lesssim A$.

Since $Z(e, v)$ was null-homologous in M^3 , each $\bar{Z}(e, v)$ is null-homologous in (N^3, hyp) . Therefore, each $\bar{Z}(e, v)$ bounds a chain $\bar{Y}(e, v)$ with volume $\lesssim h^{-1}A$.

Now the sum $\sum_e \bar{Y}(e)$ is homologous to $(deg \phi)[N]$ in $H_3(N, \mathbb{Z}_2)$. Since we assumed the degree of ϕ is non-zero in \mathbb{Z}_2 , the cycle $\sum_e \bar{Y}(e)$ is non-trivial. Using the Z 's and Y 's, we will break this cycle into small pieces.

$$\begin{aligned} \sum_e \bar{Y}(e) &= \sum_e \bar{Y}(e) + \sum_{v, e: v \in e} \bar{Y}(e, v) + \sum_{v, e: v \in e} \bar{Y}(e, v) = \\ &= \sum_e (\bar{Y}(e) + \sum_{v \in e} \bar{Y}(e, v)) + \sum_v (\sum_{e: v \in e} \bar{Y}(e, v)). \end{aligned}$$

Each term in parentheses on the last line is a cycle. The reader may check this by computing the boundaries and recalling that $\sum_{e: v \in e} Z(e, v) = 0$. One of these cycles must

be topologically non-trivial and so have volume $\geq V$. But each term in parentheses has volume $\lesssim (1 + h^{-1})A \lesssim h^{-1}A$. Therefore, $h^{-1}A \gtrsim V$ as we wanted to show. \square

This completes the proof of Theorem 4.2. \square

There are many open questions about distortion and conformal length/volume. It would be interesting to know more about the distortion of many particular knots, starting with the torus knot $T_{2,q}$. One may also ask about the distortion and conformal length of graphs embedded in \mathbb{R}^3 . Then one may ask about the distortion and conformal volume of simplicial complexes X^k embedded in \mathbb{R}^n . One may also ask about the distortion and conformal volume of higher dimensional knots.

One may also ask about the combinatorial thickness or retraction thickness of knots. There are various results involving different kinds of ‘thickness’ of knots, including [Na] and [BuSi].

5. APPENDIX: GEOMETRY AND TOPOLOGY OF ARITHMETIC HYPERBOLIC 3-MANIFOLDS

In this section, we discuss closed arithmetic hyperbolic 3-manifolds, which are a special class of closed hyperbolic 3-manifolds. Arithmetic means that the fundamental group is an arithmetic lattice in the group of isometries of hyperbolic space. This arithmetic property turns out to have important consequences in geometry and topology.

To fix ideas, we consider a single closed oriented arithmetic hyperbolic 3-manifold X_0 and then consider a sequence of arithmetic covers $X_i \rightarrow X_0$ with degree $D_i \rightarrow \infty$. The volume of X_i is $V_i = D_i \text{Vol}(X_0)$.

The arithmetic property of the sequence of covers leads to a remarkable geometric inequality about the X_i . Namely, the Cheeger constant $h(X_i)$ is bounded below uniformly: $h(X_i) \geq c > 0$ for all X_i . (The first estimate of this kind was proven by Selberg [S], published in 1965. Selberg proved that the first eigenvalue of the Laplacian $\lambda_1(X_i) \geq c > 0$ where X_i are arithmetic surfaces. A lower bound on λ_1 and a lower bound on the Cheeger constant h are closely related by the theorems of Cheeger [C] and Buser [Bu]. In particular, Buser’s theorem implies that if a sequence of hyperbolic manifolds has $\lambda_1(X_i) \geq c > 0$, then it also has $h(X_i) \geq c' > 0$. The most general theorem about arithmetic manifolds and expanders is due to Clozel [Cl].)

If we fix a triangulation of X_0 , then we can lift it to give a family of triangulations of X_i . We let Γ_i denote the 1-skeleton of the triangulation of X_i . The isoperimetric constant $h(\Gamma_i)$ approximately agrees with $h(X_i)$. In particular, $h(\Gamma_i) \geq c' > 0$ for all i . Hence the graphs Γ_i are a family of expanders.

Now we turn to the topological implications of geometric information about X_i . The first example that I know about is a theorem of Milnor and Thurston [MT], which proves that a closed hyperbolic manifold with large volume is topologically complicated. Milnor and Thurston prove that if X is a closed hyperbolic manifold X with volume V , then it takes $\gtrsim V$ simplices to triangulate X . (Moreover, it takes $\gtrsim V$ simplices to build a singular cycle homologous to $[X]$.) Their work introduced the important idea of simplex straightening.

Notice that our arithmetic X_i can be triangulated by $C_0 D_i$ simplices, where C_0 is the number of simplices needed to triangulate X_0 . Therefore, the Milnor-Thurston bound is nearly sharp: X_i can be triangulated with $\lesssim V_i$ simplices, and any triangulation requires $\gtrsim V_i$ simplices.

The work of Milnor and Thurston connected $Vol(X_i)$ to the topology of X_i . More recent work has connected the isoperimetric bound $h(X_i) \geq c > 0$ with the topology of X_i . A typical application is that for arithmetic hyperbolic 3-manifolds, the Heegaard genus of X_i is $\gtrsim V_i$.

Here is a loose sketch of the proof, emphasizing the main idea. Let G_i be the Heegaard genus of X_i . In particular, we can find a smooth map $F : X_i \rightarrow \mathbb{R}$ so that each fiber $F^{-1}(y)$ is a closed surface of genus $\leq G_i$. Next we “simultaneously straighten” all of the fibers. This step requires care and more detail, but it turns out to be morally correct. Now each fiber has area $\lesssim G_i$. One of the fibers must bisect X_i , in the sense that half of the volume of X_i lies on each side. Now the isoperimetric inequality says that $G_i \gtrsim h_i(1/2)V_i \gtrsim V_i$.

This estimate for Heegaard genus is also sharp up to a constant factor. The Heegaard genus of X_i is $\leq D_i G_0$, as one sees by lifting a Heegaard decomposition of X_0 . Hence the Heegaard genus of $X_i \sim V_i$.

An early paper with many of these ideas is [BCW], which estimates the Heegaard genus of a closed hyperbolic manifold containing a large embedded ball. Bachmann, Cooper, and White prove that a closed hyperbolic 3-manifold containing an embedded ball of radius R has Heegaard genus at least $(1/2) \cosh(R) \geq (1/4)e^R$. This number is essentially the area of a cross-section of the ball. Arithmetic examples do have embedded balls of radius $R_i \rightarrow \infty$, and so one sees that the Heegaard genus of X_i is at least V_i^ϵ for some $\epsilon > 0$.

The sketch above suggests a little bit more than a lower bound on the Heegaard genus of X_i . Namely, any smooth map $F : X_i \rightarrow \mathbb{R}$ needs to have a complicated fiber.

Complicated fiber inequality. ([Gr1]) *Suppose that X_i are arithmetic hyperbolic 3-manifolds and that $F : X_i \rightarrow \mathbb{R}$ is a generic smooth map. Then one of the fibers of F has the sum of its Betti numbers $\gtrsim V_i$.*

This inequality should be compared with the following basic inequality about expanders: if Γ_i is a family of expanders and Γ_i has N_i edges, then any map $F : \Gamma_i \rightarrow \mathbb{R}$ has a fiber that meets $\gtrsim N_i$ different edges.

Starting from here, arithmetic hyperbolic 3-manifolds can be considered as topological analogues of expanders. This point of view leads to the theorems in [Gr1] and in this paper.

It is not known whether this complicated fiber inequality (or something similar) applies to arithmetic hyperbolic manifolds of dimension $k \geq 4$.

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